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National Conference on the Interagency
Energy/Environment R and D Program Held at
Washington, DC on June 7-8, 1979

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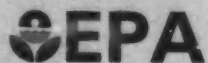
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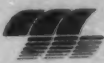
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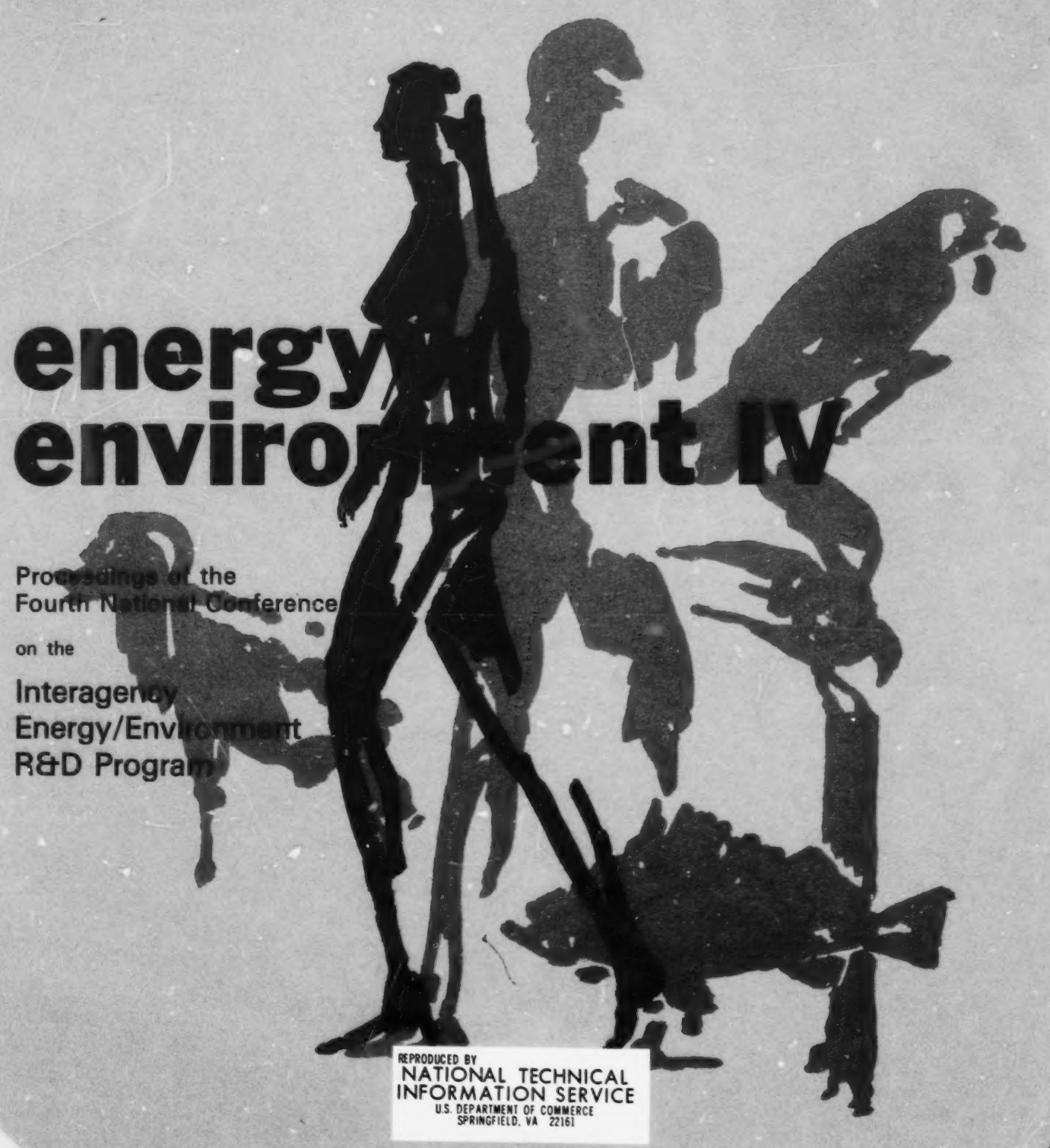
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Energy, Minerals and Industry



Decision Series 

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energy environment IV

Proceedings of the
Fourth National Conference

on the

Interagency
Energy/Environment
R&D Program

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the energy/environment R&D decision series

Some of the basic problems facing our society today involve the use of our energy resources and the consequent effects on our environment. These problems affect everyone, and everyone has an interest in their resolution. But the technical aspects of these problems make it difficult for a major portion of the interested public to understand and participate in the decision-making process. This volume contributes to the bridging of this information gap.

The Energy/Environment R&D Decision Series was inaugurated late in 1976. The series presents, in an easily understood and informative manner, selected key issues and findings of the Federal Interagency Energy/Environment Research and Development Program, which was initiated in fiscal year 1975. Planned and coordinated by the Environmental Protection Agency (EPA), the Interagency Program sponsors more than 1,000 research projects ranging from the analysis of health and environmental effects of energy systems to the development of pollution control technologies.

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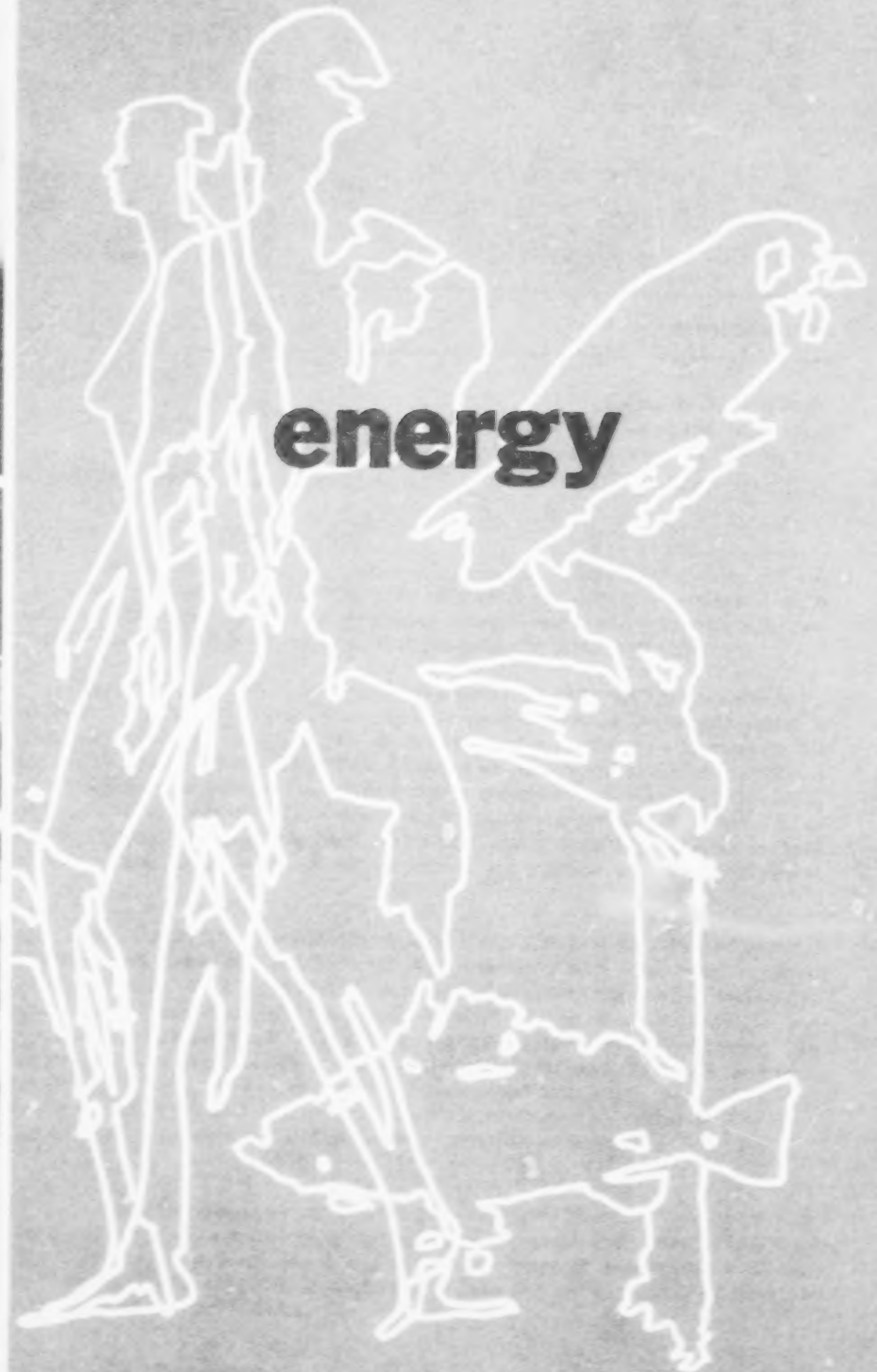
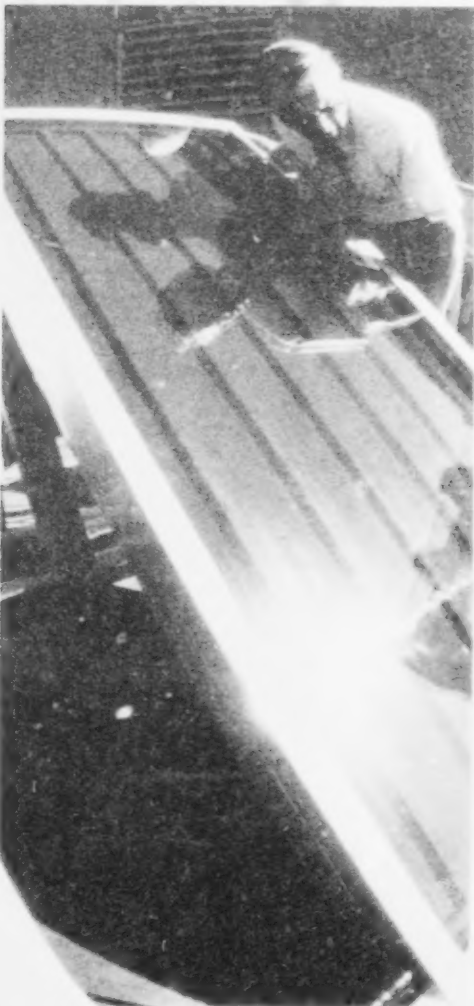
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session 1





INTRODUCTION

Steven R. Reznick, Ph.D.
Office of Environmental Engineering and Technology
U.S. Environmental Protection Agency

CONFRONTING LIMITATIONS

In December, 1973, the Arab oil embargo forced the people of the United States to confront the consequences of critically limited natural resources. We continue to experience these consequences, and increasingly to appreciate the resultant economic, political, environmental and social difficulties.

Since the initial OPEC price rise in the winter of 1974, we have experienced a wintertime natural gas shortage, an extremely serious upset at Three Mile Island, a prolonged suspension of Iranian oil production, and a continuing escalation of the price of petroleum. These events have proved so perplexing that we do not yet have a clear understanding of where our actual energy choices lie, or what the implications of those choices will be for the future of our economy, environment, and indeed all of society. Furthermore, we have been unable to translate what knowledge we do have into terms that will lead to public acceptance and ratification as national policy.

During the 30 years between the Second World War and the OPEC oil embargo certain lessons were demonstrated and redemonstrated until they were accepted without question. We learned that technological development was not just desirable or rewarding, but was absolutely essential for survival in a world of economically and politically aggressive nations committed to the full exploitation of technology. We learned that fiscal and monetary policy could control the behavior of our economy. We learned, or thought we learned, that technological innovation coupled with economic policies to ensure appropriate allocations of labor and capital could sustain natural resource development and economic growth without bounds.

CONFRONTING TRADITIONAL FAITH

The first resources to be scarce were those that were priced the lowest—clean air and clean water. The next—energy—was also priced far too low. Now, to confront these problems of polluted water and air and shortages of energy, we must first confront our traditional faith in technology, fiscal and monetary policies, and the limitlessness of natural resources.

For many years the cost of energy decreased. In the first 74 years of this century, our investments of capital and labor returned increasing amounts of useful energy in the form of electricity, home heat, and transportation fuel. The decreasing cost stemmed in part from expanded discoveries of sources of easily obtainable fuel, in part from technological innovation, and in part from investments in the production and transportation equipment capital necessary to make energy delivery efficient.

Today, the cost of new energy sources is increasing, and we face an entirely different prospect. Future investments of capital and labor will return less energy than before. In the past an hour's labor, properly divided among exploration, building capital equipment, and operating drilling rigs, would return one barrel of oil. Today, an hour's labor properly divided between building and using mining machines will produce coal with an energy content equal to about one quarter of a barrel of oil. Simply stated, we are going to use increasing amounts of our productive capacity to obtain decreasing amounts of energy. The challenge will be to make investment in these high-cost/low-yield technologies attractive.

A FUNDAMENTAL REALITY

This situation has created remarkably difficult problems for our economic and social systems. As a society, we have found it enormously difficult to accept the fact that inexpensive fuels are disappearing and that we must now not only pay more, but use less. Foreign or domestic oil interests may exploit this situation to realize large profits, but this does not deny the fundamental reality—we will have to pay more and we must use less. We must change from a society oriented to resource exploitation to one oriented to resource conservation.

The cost of the new sources of energy will be paid in part economically and in part in terms of environmental quality and occupational or public health. Both coal and nuclear power can cause widespread degradation of environmental quality and human health. Coal mining, particularly underground mining, is a dangerous occupation. Coal production can cause widespread land and hydrological disturbance. Coal combustion can generate increased air pollution. When compared with oil and gas production, the increased use of coal will accelerate the deterioration of clean air, water and productive land.

Many of the adverse impacts on health and environmental quality can be controlled or avoided. Most mined land can be reclaimed. Particulate matter and the oxides of nitrogen and sulfur can be scrubbed from flue gas. Acid precipitation and its effects on agricultural and forest production can be reduced.

Controlling these pollutants increases the monetary cost of energy, but failure to control them lowers the productivity of land resources and imperils the health of our population. We can elect to pay the environmental and public health costs of using coal now with reclamation practices and flue gas cleaning technology, or, they can be paid later with barren lands and premature deaths.

HARMFUL AND BENIGN SOURCES

Most new sources of fossil energy, e.g., oil from the Arctic or the Outer Continental Shelf, coal burned directly or processed to synthetic liquid or gaseous fuels, and oil shale, potentially threaten environmental quality. Other new energy sources such as unconventional natural gas, geo- or oceanic thermal gradients, biomass-derived fuels and solar energy seem environmentally benign. The vastness of the scale on which energy supplies will be used, however, dictates a careful and thoughtful evaluation to ensure that these sources are, in fact, developed using materials and practices that do not create environmental or public health problems.

In addition to the problems of mine drainage, disturbed land, and air pollution, coal use presents two as yet unresolved environmental questions. Mining, conventional combustion, coal processing and pollution controls all generate large volumes of solid wastes. At present too little is known about how these wastes should be handled to prevent serious future problems. We know that partial and complete combustion will form or concentrate metallic and organic pollutants in ashes and sludges. However, we

do not know the geo-chemical behavior of these materials. Processing operations require incomplete combustion and will generate pollutants that may have carcinogenic or other chronic health effects. If coal is to be the future source of liquid or gaseous fuels, we must develop a much improved understanding of health risks from the new pollutants that will be generated.

ADDITIONAL ENERGY-RELATED CONCERNS

The conversion of our automotive fleet to diesels would save energy, but diesel soot contains many of the complex organic materials that are known to cause cancer or other chronic health problems. Offshore and Arctic petroleum development introduces contaminants into particularly fragile environments. Materials such as drilling mud biocides, geological fluids and spilled oil degrade ecosystems that are vulnerable and slow to recover. Oil shale development poses environmental problems similar to those of coal including the requirements for large quantities of water. Perhaps the ultimate limit on fossil fuel use will be caused by the accumulation of CO₂ in the atmosphere. A doubling of the concentration of carbon dioxide may result in climatic changes. Expanded use of coal and oil shale could produce these changes in the beginning of the next century.

The reality of diminishing supplies of petroleum and natural gas will change our society. The rate of change and the future form of society will be determined by the choices we make now. One of those choices will be how to apportion the costs between pollution controls and environmental impacts. Of late, a note has crept into energy discussions that is contrary to good decisionmaking and responsible public policy. Environmental concerns are being unfairly blamed for blocking energy development, when in actuality the problem appears to lie in the uncertainties of investment. For example, discussions in the press of the Tellico Dam decision, the Sohio pipeline, and the New Source Performance Standard for coal combustion have been less than comprehensive or well-informed and have failed to report all the economic and environmental considerations.

ENERGY/ ENVIRONMENT

The Interagency Energy/Environment R&D Program was designed to provide for the exchange of information needed for knowledgeable decisionmaking. At this, the Fourth National Conference on the Interagency Energy/Environment R&D Program, we will explore our present understanding of many of the issues concerning the use of our remaining supplies of nonnuclear fuels. The purpose of the conference is to provide the information necessary for making better choices between meeting control costs now and paying for impacts in the future. Research will generate the knowledge needed for decisionmaking. Proper discussion of the available knowledge in forums such as this will lead to unprejudiced decisions that best serve the public interest.



The Honorable Max Baucus

KEYNOTE ADDRESS

The Honorable Max Baucus
United States Senator From Montana

Thank you for your warm welcome.

REEXAMINE AND REDEFINE

When asked to speak at this conference, I realized that there are no two words whose meaning has changed more in the past decade than *energy* and *environment*. As I prepared for this speech, I was forced to reexamine and redefine what these words mean.

Growing up in Montana, I felt the pride in the out-of-doors that most Montanans feel. I could walk to a stream, bend down, and drink the water as it flowed by. I remember herds of deer and elk in the valleys right near my parents' ranch outside Helena. And, of course, I was never more than 15 minutes from a good trout stream.

A NEW CONSCIOUSNESS

Today there is a new consciousness in Montana. The President's decision to decontrol the price of oil means that previously marginal oil reserves now become productive, and rigs are springing up all over the state.

Eastern Montana's plains contain some of the world's richest deposits of strippable coal, and massive equipment is peeling away much of the land. How will development of these resources, so vital in our national energy picture, affect the countryside of my state? That's the question many Montanans are asking.

Not everyone is as lucky as I have been. Not everyone enjoys tromping through a mountain valley where the only other creatures are the birds and animals who live there. What happens, though, when some geologist discovers oil in that mountain valley and the hills are dotted with drilling rigs and the streams become filled with drilling wastes? Is that oil worth the destruction to the valley? What price are we willing to pay for energy? These are the central questions we must ask ourselves. These are the questions that perhaps more than our supply of gasoline will determine how enjoyable our lives are in 5, 10, 25 and 50 years.

If we have learned anything in recent years about increasing energy production, it's that we must not develop energy resources without fully considering the risks they may cause to our environment. Whether it is nuclear waste from Three Mile Island, waste from oil drilling rigs, or sludge from coal, we have learned that lesson the hard way. There is waste material produced from producing energy, that's for sure. As more and more energy is consumed to produce more and more products, more and more toxic waste is produced.

HORROR STORIES

You all know the horror stories: radiation leakage at Three Mile Island, PCB's strewn along North Carolina roadsides, Love Canal, and on and on. American industry generates about 100 billion pounds of hazardous wastes every year. That is about the total weight of every car now on the road. But only 10 percent of those wastes are disposed of properly. The rest are buried somewhere threatening to poison the water we drink, the air we breathe, the food we eat. It's a time bomb just waiting to go off. No one knows where or when that's going to happen. I don't think I'm telling you anything you don't already know. Nor do I believe you are willfully ignoring the importance of our problem. But that doesn't alter my conclusion: The Federal Government does not have a comprehensive, aggressive strategy to defuse that bomb.

AVAILABLE LEGAL TOOLS

We don't need new legislation. The Safe Drinking Water Act, the Toxic Substances Control Act, the Clean Water Act, and the Clean Air Act were enacted in response to growing evidence that we were polluting our environment. There are 21 Federal statutes to combat the hazards of toxic waste from uranium mill tailings to lead-based paint, and criminal penalties are prescribed for violators of these acts when they engage in conspiracy or fraud. We don't need new laws. We must simply enforce the laws already on the books. Legal tools are available. They are not being used. The financial incentive to dump toxic wastes is high, but the risk of prosecution is not. Why aren't these tools being used? In April, I chaired a hearing to look into that question. We found that the Justice Department has only one full-time attorney to prosecute hazardous waste cases. That's not just the Hooker Chemical/Love Canal case—that's all hazardous waste cases. Hooker Chemical, on the other hand, has hired three law firms for its defense against the government. I don't think the Federal Government and the people of the United States have much chance against those odds. It's a little like Calvin Murphy trying to guard Wes Unseld, Bobby Dandridge, and Elvin Hayes at the same time. The Government's litigation staff is pitifully inadequate.

The problem is compounded by EPA's delay in promulgating regulations under the Resource Conservation and Recovery Act of 1976. The regulations under this act—potentially the most powerful weapon in the battle—will not be completed until December of this year, more than a year-and-a-half late. These regulations will, of course, be subject to court challenges. To survive any challenge they must be in accord with Congressional intent. We can't afford to have the regulations thrown out completely, as in the case of the Clean Water Act.

INVESTIGATIVE STRIKE FORCE

Nevertheless, there are a few things we can do. First, the key to any successful prosecution is thorough, competent investigation. Polluters and dumpers won't be deterred unless the government wins the cases in court. But, incredibly, EPA has yet to hire a single investigator with law enforcement training. That's an institutional failure of massive proportions. EPA estimates there are over 2,000 hazardous waste dumps across the United States that pose an imminent and substantial danger to public health. With a threat that large, EPA desperately needs an investigative strike force, and their training should be comparable to that given FBI or IRS agents. Investigators should be capable of identifying hazardous waste dumps, tracking down the owners, or former owners, and establishing whether organized crime is involved.

LAW ENFORCEMENT ETHIC

Second, the strike force should be guided by a professional law enforcement ethic. To me that means a commitment to tough, uncompromising investigations—a willingness to follow through until the job is done. It's an attitude that must be established at the beginning. All too often the Federal Government is willing to settle cases out of court—to negotiate a civil remedy when criminal sanctions are clearly called for. EPA and the Justice Department must demonstrate that they are willing to go to the mat on these cases. It's time to serve notice that the law enforcement agencies of this government are determined to prosecute to the fullest extent of the law those who willfully violate our country's antipollution statutes. The only way to defuse a time bomb is to have the courage and resources to take the bold steps necessary. The battle against environmental terrorism cannot be fought with timidity or a strategy of compromise.

COORDINATION OF FEDERAL AGENCIES

Third, coordination is a crucial factor in any effective law enforcement program. Several agencies of the Federal Government already are involved in different aspects of waste management. For example, the Bureau of Alcohol, Tobacco, and Firearms has jurisdiction to investigate hazardous wastes wherever there is a threat of explosion. That's the case in Elizabeth, New Jersey, where a warehouse is filled with corroded drums that are leaking toxic chemicals. Who knows how many people might be injured or killed? Sites posing this kind of threat should be identified immediately and the Bureau of Alcohol, Tobacco, and Firearms should be called in to investigate wherever its jurisdiction warrants. Moreover, the Department of Transportation's Bureau of Hazardous Materials Transportation should be called in wherever its jurisdiction warrants.

In addition, greater cooperation with all the states should be encouraged. State highway patrols could monitor roadside dumping of hazardous wastes. Local health officials could monitor toxicity levels in the local water supply and report their findings to EPA. I would also like to point out that each citizen has a role to play in the enforcement of pollution control. It should be remembered that the successful prosecution of those responsible for dumping thousands of gallons of PCB's along North Carolina highways was initiated by one alert, concerned citizen.

HAZARDOUS WASTE HOTLINE

Perhaps the EPA and the Justice Department should establish a hazardous waste hotline so that citizens can alert the government to surreptitious dumping and provide evidence of illegal waste management practices. The American people have every right to expect that our nation's laws controlling pollution and waste will be vigorously enforced and I am convinced they, too, will play their part in this crucial effort. We must remember, regulations are only part of the answer. We must clean up the present regulatory process. Too often delays caused by a cumbersome bureaucracy thwart efforts to enforce the law.

THE STAKES ARE HIGH

The stakes are high. Each generation of Americans becomes the custodian of our natural resources. Each generation, in turn, has the obligation to pass this inheritance on to future generations. Is Montana going to lose its pristine valleys and trout streams before my son is old enough to enjoy them? Or, will we strike a balance where these invaluable and irreplaceable resources are protected? Finding that balance and being willing to act with courage and fairness is our challenge.



Donald M. Kerr, Ph.D.

OVERVIEW ON ENERGY FUTURES

Donald M. Kerr, Ph.D.
U.S. Department of Energy

SERIOUS DEBATE

Since the oil embargo of 1973, the American people have engaged in an increasingly serious debate over oil supply and prices. Our standards of living have been called into question as world oil prices have risen and relative world supplies have either decreased or remained stagnant. There is an emerging consensus that we must reduce our oil import bill which is draining over \$50 billion a year from our economy. What we do not have, however, is a consensus of how we should go about this task. The President's National Energy Plan sets two cornerstones upon which we can build toward this goal. The first is conservation and the second, to which I will address myself, is the increased usage of coal and other alternative energy sources.

Given the meager prospects for improvement in world oil supply and the long leadtimes for the introduction of other alternatives, the United States will require much greater use of coal in order to grapple effectively with the energy problems of the 1980's and 1990's. Without greatly expanded use of coal, this country just may not make it. In the abstract, the need to increase coal production and use is recognized by all. In practice, countless decisions, arrived at independently by various levels of government, tend to militate against the use of coal. If this Nation is to cope effectively with economic and national security problems during the rest of this century, the obstacles to increased coal production and use must be removed by an effective national commitment to coal.

OIL IMPORTS

Two years ago the President presented the National Energy Plan (NEP) to the American public and to Congress. The NEP proposed measures that would keep oil imports at 6 to 7 million barrels per day (MMBD) in 1985. While many of these measures were enacted, three elements critical to greatly increased coal use have not been implemented:

- Domestic oil and gas prices have not moved rapidly to world levels.
- An industrial user's tax and rebate mechanism, reinforced by a regulatory program, was not enacted.
- A stable regulatory regime has not been established.

SOMBER ASSESSMENT

As a result of these and other factors, the use of coal in 1985 is expected to be substantially less than projected earlier and the demand for imported oil higher by at least 2 MMBD. At the same time, developments in the world oil market have made it increasingly doubtful that an additional 2 to 3 MMBD will be available.

The extended curtailment of Iranian exports and the reduced level at which production was resumed have brought closer the time when world oil demand exceeds available supply. There have been no other developments that have favorable oil supply implications for the near- or long-term. This more somber assessment of world oil prospects is based on the following considerations:

- The situation in Iran has not stabilized and current exports of 2 to 3 MMBD could be stopped again at any time.
- Saudi Arabia has delayed capacity expansion and has imposed restrictions on production.
- Elsewhere in OPEC, no additions to capacity can be anticipated and current capacity continues to erode due to maintenance difficulties and maturing fields.
- The disappearance of spare capacity makes the U.S. more vulnerable to random disturbances in the intricate global oil supply system. The Nation is also more vulnerable to politically-inspired embargoes, imposed by any one of several small producers, that would have been little more than an inconvenience a few years ago.
- Outside of OPEC, no new oil provinces have been discovered, despite continued drilling, to supplement the last large finds in the North Sea, North Slope, and Mexico; and there is no improvement in the energy outlook for the Soviet Union.
- The position of the price moderates in OPEC has been weakened by the change in Iran and the successful demonstration that less oil brings more money.

LESS OIL IN THE 1980'S

Consequently, there will be even less oil in the 1980's than was expected 2 years ago and quite possibly no more than is available today. If additional oil is not available, increased demand will push world oil prices up causing higher rates of inflation and reducing output and employment. Under these circumstances, further increases in U.S. oil imports could be obtained only by bidding available supplies away from Europe, Japan, and the less developed countries. If further increases in oil imports are not available on acceptable terms, our Nation will have to meet its additional energy needs from domestic resources. Although conservation has reduced growth in energy demand to half the rate of GNP growth, there is still a great demand that must be met by domestic production. Domestic oil and gas output cannot be expected to increase sufficiently, even with greater investment. The use of solar and renewable energy resources will increase steadily in coming years, but long leadtimes in developing and placing these new technologies in commercial use will push their main contribution into the next century. Finally, increases from nuclear power may be reduced as a result of Three Mile Island. The only conclusion that can be drawn is that coal must play the major role in meeting the Nation's incremental energy needs for the rest of this century. The alternative is no longer imported oil because it will not be available. The only other alternative is a permanent slowdown of the economy.

LAGGING COAL GROWTH

Notwithstanding the critical need for coal, growth in domestic coal use is lagging. To meet the Nation's energy needs, coal consumption will have to have risen from 623 million tons in 1978 to 1.0 billion tons by 1985 and 1.6 to 2.1 billion tons by 2000, depending on the contribution of nuclear power. This will require at least a 4.5% annual increase in coal use. Yet, over the last 5 years, annual growth has averaged 2%, and has even been less in recent years. The difference between a 2% and 4.5% annual rate of growth in coal use by the year 2000 is approximately 600 million tons of coal or the equivalent of 6 million barrels of imported oil per day. Additional oil in that quantity is not likely to be available. Two major factors will determine how

quickly and to what extent we may make use of our abundant coal supplies. The first is economics; the second; environmental regulations and technology.

ECONOMICS

In terms of economics, the critical factors will be the relative cost of synthetic fuels produced by coal and future world oil prices. The current world market price for oil is approximately \$16-\$17/barrel. The current estimated cost of synthetic fuels from coal ranges from \$23-\$35/barrel. Therefore, although the economics today do not seem to make sense, viewed in the perspective of unpredictable rises in world oil prices and the leadtimes needed to construct and put on-line synthetic plants, the critical decision time for the U.S. is now. The economics of alternative energy sources such as synthetic fuels from coal and alcohol fuels cannot be judged on a strict dollar-for-dollar basis with world oil prices. We must also look at the drain on our domestic economic resources which our huge oil import bill causes. We must ask ourselves the question: Is \$17 a barrel paid abroad really cheaper than \$23 a barrel paid into the U.S. economy?

Until the year 2000, close to 90% of all the coal consumed in this country will be burned directly. Therefore, a primary objective of our national coal program is to ensure that environmentally sound technologies are available to allow us to burn this coal. The economics of liquefaction technologies are issues which must be resolved in the 5- to 10-year period to come. An immediate hindrance to the increased usage of coal must be addressed if we are to build upon the cornerstone which the NEP has laid.

There is an unavoidable conflict and a need to balance the necessary increased usage of coal with air quality. If the Nation is to have reliable sources of power, then hard decisions must be made. The environmental control technologies which we are pursuing can help to alleviate much of the conflict but the State and Federal Governments must realize that in the short term, technology is not the total answer. The balance between increased coal usage and environmental integrity is not one which can be struck entirely at the national level. In many cases, individual states have passed air quality control standards more stringent than the national ambient air quality standards. Some thought must be given to relaxing these standards if increased coal usage is to be achieved.

ECONOMIC INCENTIVES

We must also consider economic incentives and depreciation allowances in order to promote the usage of coal as a boiler fuel in existing facilities. In a similar vein, the Federal Government must seek to streamline licensing procedures for coal-fired utility and industrial users of coal.

There is a limit to what the Department of Energy can do by itself. We can seek to speed up the licensing of such plants; to increase coal production; and to improve technologies such as atmospheric fluidized bed combustion and advanced control technologies, but other elements of the Federal government, such as the Environmental Protection Agency, the Department of Transportation and the Department of Interior, also have significant roles to play if we are to obtain our goals of increased coal utilization.

ADVANCED ENVIRONMENTAL CONTROLS

Three methods of removing pollutants from coal exist:

- Coal cleanup (examples are chemical and physical preparation)
- Combustion techniques (examples are atmospheric and pressurized fluidized bed, and MHD)
- Flue gas or gas stream cleanup (key areas addressed in environmental control technology program)

In order for these systems to become commercially practical, careful control must be maintained of the type and amounts of impurities in the gas which can be accepted without undue corrosion, erosion, and/or contamination of system components. Requirements in this area may, in fact, be more severe than EPA emission standards,

especially in the area of particulates. DOE's funding for this area increases from \$2.4 million in FY 1979 to a request of \$10.4 million in FY 1980.

CLEANUP SYSTEMS

Efforts are oriented primarily toward turbine cleanup systems and molten carbonate fuel cell cleanup systems. Both hot low-Btu gasifier/gas turbine and pressurized fluidized bed/gas turbine systems will be studied. The aerodynamics/materials problems linked to the high-speed turbomachinery do not exist with the fuel cell; however, the molten carbonate fuel cell is susceptible to catalyst poisoning, electrode damage, and electrolyte contamination.

Flue gas cleanup and gas stream cleanup, along with technology support, bring the total budget request for FY 1980 to over \$43 million, a 600% increase over the 1979 amount—the largest growth in the FY 1980 DOE budget. Since improvements in flue-gas cleanup technology can have an immediate application commercially, DOE has accelerated its program in this area. Funding has been boosted from \$2.7 million in fiscal 1979 to a request of over \$25 million in fiscal 1980.

Efforts are concentrated in three areas:

- Advanced flue gas desulfurization
- Advanced flue gas cleanup
- Lime/limestone scrubber reliability

FLUE GAS DESULFURIZATION

Advanced flue gas desulfurization projects will evaluate a number of potential processes, many of which are sufficiently developed to permit a narrowing of choices for application in early 1982 through 1985:

- One of the advanced scrubber technologies incorporates scrubbing the flue gas with a solution quite similar to conventional lime/limestone slurries, but then regenerating the scrubbing solution rather than discarding it as a sludge. The primary by-product is sulfur dioxide, which can be converted into sulfuric acid or elemental sulfur. Capital costs of the more complex process are generally higher, but operating costs potentially can be reduced if the sulfur by-products can be sold.
- Systems using a dry material to absorb the sulfur pollutants from coal burning are also showing promise. Candidate materials include limestone, nahcolite (a natural sodium bicarbonate), trona (a natural hydrous sodium carbonate), and high alkali fly ash. These processes produce a dry solid waste with no sludge disposal problems.
- A third process uses a clear liquid, usually a sodium-based solute, to remove the sulfur dioxide. By adding lime or limestone to the liquid after it has been in contact with the combustion gases, the sulfur can be removed as calcium sulfate, a relatively benign substance which can be used as a landfill material, as a soil conditioner, or in building materials.

FLUE GAS CLEANUP

Advanced flue gas cleanup includes methods of removing or minimizing nitrogen oxides, along with particulates and trace metals. Primary focus is on developing advanced centrifuge methods, filters, and electrostatic precipitators based on conventional systems. An activity is also being conducted to evaluate new ideas for removing sulfur from hot gases, including the use of irradiation techniques using electron beams, lasers, or plasma-jets. Currently about 40 utility-size flue-gas cleanup facilities are operating in the U.S. and about 100 more are being built or designed.

Combined-cycle generating plants powered by high-temperature, low-Btu gases from direct coal gasification or high-temperature gases from pressurized fluidized bed combustion may prove to be an extremely attractive approach for large-scale coal use.

WET SCRUBBING

The most widespread application of flue gas cleaning is wet scrubbing. A water slurry of lime or limestone is brought into direct contact with the combustion gases, typically in a spray tower or similar device. Sulfur is removed mainly as calcium sulfite and in the form of a wet sludge. Sludge disposal costs represent up to 20% of the capital and operating costs of a flue gas desulfurization system. Sludge is difficult to concentrate and solidify and requires large amounts of land and careful management to avoid soil and water pollution. Methods of chemically treating the sludge to produce suitable landfill material are often prohibitively expensive, and there are doubts about their long-term effectiveness in cool climates.

The strategy in improving lime/limestone scrubbing reliability is, first, to collect, correlate, and evaluate detailed experience and then conduct parallel experimental programs using eastern and western coals. Three 10-megawatt scrubbers at the Tennessee Valley Authority's Shawnee facility in Kentucky will be used to support eventual field tests of equipment to increase reliability.

RENEWED COMMITMENT

The President has stated clearly and bluntly that the Nation's energy problems are serious and getting worse. To help solve those problems, it is imperative that the United States stop using so much petroleum and start using more abundant fuels. Although the contribution of nuclear power, solar energy, and renewables will be helpful, the greater use of coal is indispensable. If this Nation can overcome the unintended obstacles to greater coal use, then the prospects for our security and well-being are reasonably good. The time is right for a renewed commitment to coal.



questions & answers

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QUESTION

Regardless of public concern about nuclear energy, it seems courageous to face the energy problem head on and expand nuclear energy as well as coal, recognizing that it is in many ways more environmentally acceptable than coal and is a workable technology. In view of the urgency for energy, how can the administration continue to place nuclear energy in the same category with solar energy, which is some distance in the future?

RESPONSE: Dr. Donald M. Kerr (DOE)

The Department of Energy (DOE) is pursuing nuclear as one of many alternatives for the future. Nuclear technology that could be deployed now has already been developed. In fact, there are reactor vendors in the private sector and the Nuclear Regulatory Commission is available to license power stations as they are built. We, therefore, are not investing R&D funds in the present commercial versions of light water reactors, other than in some generic studies in three specific areas: (1) more efficient utilization of uranium within those reactors to make the cost of power less and reduce the requirement for uranium, (2) improvement of light water reactor safety, and (3) design improvements to reduce radiation exposure for workers in the nuclear industry. Under our congressional mandate, we are, of course, continuing to

develop an advanced breeder reactor. The point is that incremental increase in the energy supply will come through deployment of coal technologies in the near-term because we can build those plants faster than we can build new nuclear generating capacity. We do believe, however, that it is important to maintain the nuclear generating capacity now in place and also under construction because we don't have any alternative to it at the present time.

QUESTION

A good article about Mexican oil appeared in Science magazine in the fall of 1978 and another in Current History last February. Dr. Maki, whose area is economics and international law, assumes that Mexican oil reserves are roughly equivalent to the reserves in Saudi Arabia. He says that the discovery of enormous amounts of crude oil and natural gas in southeastern Mexico raises the possibility that, for at least the next 20 years, the United States can simultaneously reduce its consumption of insecure oil imports and cut back sharply on the size and intensity of its commitment to perfecting either or both of its alternate energy options, nuclear and coal. Is Dr. Maki that far off, or is this something which is coming up and may have greater importance in the future than we now realize?

RESPONSE: Dr. Kerr

As I am responsible for energy technology, I can't comment responsibly about the amount of Mexican oil. The geologists and those doing the drilling in Mexican reservoirs will know best whether it is there, and produceable. As there are uncertainties about both the supply of Mexican oil and, more importantly, the Mexican Government's willingness to make it available to the United States, I believe there is in no way a lessened need for us to develop domestic alternative sources. You might write to DOE's Assistant Secretary for International Affairs for a statement concerning the position of the Department on this subject.

QUESTION

We have heard about the need for utilization of coal but no mention of conservation as a principal means of reducing the urgency of the situation. It would seem that conservation might provide one of the largest single ways of meeting the emergency and yet in our study of the conservation education program of DOE last semester, we found that it was woefully inadequate, almost nonexistent. Would you comment on the Department's position concerning conservation?

RESPONSE: Dr. Kerr

Although I primarily emphasized the need for alternative energy supplies this morning, DOE stresses conservation. These are the two cornerstones of the National Energy Plan. It is through implementation

by industry, in particular, and not necessarily by DOE, that the one-to-one relationship between energy supply growth and GNP growth has changed so that increments of roughly one half are now involved. We have an Assistant Secretary for Conservation and Solar Applications to effectively communicate a conservation ethic and implement it in terms of new plants, new industrial processes, and particularly in new ways of living our private lives, which is very difficult. Many dedicated people in the Department support conservation as the nearest-term energy supply.

QUESTION

Is all of the Federal support for research and development for energy done through DOE?

RESPONSE: Dr. Kerr

The majority is, although other departments fund programs. NASA, for example, has direct appropriated funds for energy research, the National Science Foundation conducts basic and exploratory work, and the Environmental Protection Agency (EPA) and the Department of Interior are also active in the energy field. The Department of Transportation is pushing hard for improved efficiency in automobiles and transportation systems. Furthermore, many states have invested their own funds in energy research and development and frequently we are able to enter into partnership with them on particular projects. Although DOE is the dominant Federal agency involved, there are many others participating as well.

QUESTION

Is there an available source that gives a comprehensive picture of the financial investment of the Federal Government in the various energy fields, such as solar and wind, and other energy R&D investments?

RESPONSE: Dr. Kerr

When our fiscal 1980 budget was presented to Congress, there was a briefing sent with it. It attempted to aggregate not only the DOE-proposed investments, but those of some other agencies as well. With respect to solar, for example, there is a direct investment in R&D but in addition, there are tax credits that have been made available that must be considered in coming up with the total Federal investment which presently approximates \$1 billion.

QUESTION

Dr. Kerr, your summary of utilization targets and control technology ideas for increased coal utilization seemed to focus mainly on the electric power sector. Would you comment on coal utilization and control technology targets for what may be the more critical oil-using sectors of transportation, space, and process heating?

RESPONSE: Dr. Kerr

One reason the Department is pushing very hard to develop synthetic fuels from coal is to serve those other market sectors. We are working on direct usage of coal for industrial process heat applications, but a greater need is to displace imported petroleum in the middle distillate and ultimately in the gasoline markets. To that end, we have solvent refined coal pilot plants under construction. Plants such as the Exxon solvent plant and the H coal plant in Kentucky should not be viewed as synthetic gasoline plants, as they produce a wide range of products such as a material equivalent to residual oil. In the pilot plants, we are investigating ways to alter the slate of products and to maximize those in the middle distillate region.

QUESTION

We have a strong conservation program in the churches and the synagogues comprising the Interfaith Coalition on Energy. Some of us in the Coalition are particularly concerned that DOE and, for that matter, even EPA have not taken a serious look at the coal reactors that are based on blast furnace technology. Enclosing blast furnaces helped clean up the city of Pittsburgh, which demonstrates the value of the technology. The reactor burns the lowest grade, high-sulfur coal in an enclosed system, producing heat, steam, and electrical generation in the daytime and at night a gaseous fuel to be stored or distributed. There is no smoke stack to spew out sulfur-bearing compounds. The residue is not an ash to be dumped but a slag to be used for such things as construction material, cinder blocks, paving streets, or possibly encapsulation of noxious wastes such as those at Love Canal. DOE talks about scrubbers and cleaning up flues, when there has been a system before them for 2 years that doesn't have a flue, doesn't need scrubbers, and doesn't require the disposal of ashes. Why hasn't the proposal for this proven system been addressed by DOE?

RESPONSE: Dr. Kerr

You have described a pyrolysis system. One attractive aspect about this system is that although it does yield heat and consequently steam, and environmental emissions can be controlled, it doesn't do what is most needed right now in terms of entering, for example, the distillate market. Hydrogen has to be added to coal to get better fuels. A totally enclosed plant very similar to what you have just described and in which hydrogen is added to the coal will give a mixture of products that includes liquids and clean solids. If the next phase of the plant is properly equipped, the sulfur can be precipitated out and the end product will be a slag. There is no question that there are attractive, totally enclosed processes that would reduce emissions. The reason for focusing on flue gas cleanup and the like is to find ways to use existing installed plant capacity. As we become able to afford new plant capacity we will look to some of these advanced methods.

COMMENTS

There are those of us who consider the use of nuclear power to be detrimental to human health. My suggestion is that in the future every plant utilizing nuclear power be labeled as doing so, thus allowing the public to make an informed decision about whether they wish to invest in a particular stock.





Ruth C. Clusen

ENVIRONMENTAL AND HEALTH EFFECTS RESEARCH: THE VIEW FROM DOE

Ruth C. Clusen
U.S. Department of Energy

TEST OF COMMON SENSE

My office recently received a Freedom of Information request that was a bit unusual. The writer, who claimed to be an environmentalist, wanted a list of three valid laws that could not be carried out because they failed to meet the test of common sense. I can't tell you yet what our answer will be. The lawyers are still looking at it. But the writer may have a point: Do our environmental laws always make sense? As one who is sworn to obey the laws of the land, I cannot do other than uphold, to the best of my ability, the statutes that come within my purview. Nevertheless, I can understand why the common sense quotient of some legislation might be questioned.

RUNAWAY REGULATION

A former Deputy Administrator of the Environmental Protection Agency, John Quarles, recently wrote an essay for the Washington Post headlined "Runaway Regulation? Blame Congress." I shall not comment on his argument that Congress is at fault for the proliferation of regulations. He says the implications of statutes seldom are understood fully at the time of enactment. The result is that the public rebels, he argues. Mr. Quarles made a point in his essay that I believe is worth quoting. He wrote: "The irony—and the tragedy—of these characteristics of regulatory legislation is that they generate criticism of the basic regulatory programs despite the fact that those programs may be entirely sound. In the environmental area, progress toward control of pollution would be impossible without strong regulation. The principal programs do make sense . . ."

Congress, which was designed to be a representative body, does indeed represent the American people. Many in this country argue with the content of our laws. Few argue, however, with the basic goals of those laws. And that is the test of our form of representative government.

THE CAUSE IS RIGHT

People want a clean, safe, healthy environment in which to live. And they want it to stay that way for their children and grandchildren. The instinct of self-preservation is manifest in mankind's concern for future generations. Despite the implicit argument of the Department of Energy's correspondent that there are laws that do not make sense, I believe that he will receive no list from DOE. Sure, we have done our bit in pushing the Federal Register past 27,000 pages in 1978, with

perhaps a higher number this year, but the cause is right. Clean air, clean water, and clean soil are necessary for this generation's well-being and for that of succeeding generations. The laws do make sense. We believe that. And we must administer them in that belief. For there are no more common-sense goals than maintaining energy supplies and improving our environment.

The first day's program of this Fourth National Conference emphasized the efforts of EPA and DOE in the search for compatible solutions to the energy/environment dilemma. Today's program emphasizes environmental and health effects of energy research and development. The hypothesis that a dilemma exists seems to be countered by the existence of research aimed at saving us from that seeming predicament. Does this nation, through its government, really have to choose between two separate but equal propositions? Is it really either all the energy we can produce with concurrent filth and hazards or pristine safety with creeping starvation? Is it DOE versus EPA in the gladiatorial ring? Obviously the answer to all those questions is no. If the answer were yes, we would not be participating in this joint conference.

MELDING SEEMINGLY CONFLICTING GOALS

The fact of this conference also means, however, that there are big problems in melding energy and environmental goals. That's why EPA in its pursuit of environmental protection contains units concerned with energy production. In like manner DOE, in its pursuit of energy development has programs aimed at protection of the environment. And both agencies have been instructed by the people's representatives to work out that melding of seemingly conflicting goals while at the same time sidestepping economic pitfalls. Let me be candid with you. My Office of Environment is part of the Department of Energy. My office shares the mission of DOE to make sure that this country's energy needs are met. Some call my office the millstone around DOE's neck. Others would call us sycophants. But the best way to state our job is to quote the Energy Organizational Act of 1977. That law says that the ultimate goal of the Office of Environment is "to assure incorporation of national environmental goals in the formulation and implementation of energy programs, and to advance the goal of restoring, protecting, and enhancing environmental quality, and assuring public health and safety." And I say that is just common sense.

ACTION IS DEMANDED

There are and should be no conflicts between our agencies or any others within the Federal establishment. Yes, there are difficulties in policymaking. But the cynical response of doing nothing is not permitted. There must be trade-offs. The law demands trade-offs. The courts cannot decide, because these are basically political questions. Politicians constantly risk their careers trying to balance goals that seem at odds. Action, any action, will arouse opponents. Yet action is demanded, and it is taken. Government employees, for the most part, are outside partisan politics. But they are part of the American body politic. They are paid to make tough decisions in fulfilling the laws they administer. They must analyze the issues and communicate that analysis to all levels of public and private communities. And they must make sure that the effects of policy decisions are founded on careful and comprehensive analysis.

That quality of decision cannot be reached without superior research findings. We in the Office of Environment strive for superior research. Right now a committee from the National Academy of Science is looking at the quality of our research into the health effects of low-level ionizing radiation. A report is due this summer. DOE's nonnuclear energy research bylaw is subject to a continuous review by another agency, now the EPA. This year EPA is looking at DOE's environmental planning and review procedures. DOE is working with EPA, the Department of Transportation, and the National Institute of Occupational Safety and Health on the emissions of diesel engines. Those are three examples of how the Office of Environment is reaching for quality in its research efforts.

NATIONAL ENERGY PLAN

The President's second National Energy Plan constitutes marching orders for the Department of Energy and its components. The plan anticipates that decontrol of domestic oil prices will restrain the overall use of oil by reducing its importation and stimulating production at home. That should increase reliance over the coming years on coal and nuclear power, and bring on the development of a shale-oil industry.

Those developments will make necessary intensive efforts to resolve the environmental problems connected with the use of those fuels.

SYNTHETIC FUELS

Some synthetic fuels, such as shale oil and coal liquids and gases, are expected to become economically attractive in the '90s. The air pollution that could be caused by the burning of those fuels will have to be controlled. Water problems are associated with the production of shale oil. Large quantities of water will be consumed in mining and processing the oil shale, disposing of waste, and in replanting stripped areas. In addition, there are problems with water supply contamination. Synthetic fuels based on coal will require increased mining, and the processing can result in the release of toxic substances inside and outside the plants. Actual environmental effects are still uncertain because no commercial-sized plants have been built. Research is underway, however, to develop information on which to base standards and controls for protecting public health and safety.

The major unresolved technical problem of nuclear energy is the disposal of radioactive wastes. Also, the siting and operation of nuclear plants must be done with care because of public concern with radiation releases.

Solar energy is relatively benign for environmental purposes when compared with conventional fuels. Some solar processes, however, could consume significant amounts of water or use large land areas. And combustion of biomass adds carbon dioxide to the atmosphere.

We in the Office of Environment have the lead among Federal agencies in research on the effects of increased CO₂ levels in the atmosphere. In the last century and a quarter the amount of carbon dioxide in the earth's air cover has gone up by 10 percent. About one-fourth of that increase has occurred within the past 10 years. If the trend continues, it is conceivable that the levels could increase by two or three times in the next century. Existing computer models predict a 2°C to 3°C rise in the average surface temperature for each doubling of the carbon dioxide level. We must know more about this phenomenon; thus the research effort.

EMISSION PROJECTIONS

Other air emissions are known to be environmentally hazardous. The Clean Air Act Amendments of 1977 call for stricter emission controls by 1985. Enforcement of those will reduce emissions of particulates, hydrocarbons, and carbon monoxide by the year 2000, according to projections. Sharp reductions are expected in particulate emissions through the upgrading of controls on existing and new coal-fired generating plants and industrial boilers. Sulfur oxide emissions in 2000 are projected to be the same or slightly less than in 1975. Increases in sulfur dioxide from coal burning would be counteracted by improved efficiency in control devices. Total nitrogen oxide emissions are expected to increase by more than 30 percent by the turn of the century. In certain regions, nonattainment of air quality standards, or regulations prohibiting significant deterioration of air quality, may restrict energy development.

Water pollution remains a widespread problem despite national efforts that have improved water quality during the last decade. The nation's energy needs are expected to quadruple water consumption by the end of this century. Coal mining and processing operations could cause substantial increases in total dissolved solids releases. Other releases into waterways would be of oil, greases, and sulfates. Total dissolved solids are projected to double by 2000, but total suspended solids are expected to decrease slightly. Nutrients and biological energy demand from energy sources are projected to remain near their 1975 levels.

SOLID-WASTE PROJECTIONS

Now to turn to solid waste. Noncombustible solids currently remaining after conversion of solid fuels and sludges from energy-related pollution control devices account for about 17 percent of all solid waste produced in this country. Projections for the end of this century show increases of several times as the result of greater coal usage. Challenges are posed for dealing with larger landfill volumes, leaching and transport of undesirable contaminants, and disposal of hazardous wastes.

RADIOACTIVE POLLUTANTS

What about radioactive pollutants? The energy plan projects nuclear power plant increases from threefold to sixfold by 2000. Three types of pollutants must be handled: solid wastes such as spent fuel and reactor parts, liquid waste containing low levels of pollutants from nuclear plant cooling, and, finally, reactor off-gases. The combustion of coal and oil may also produce radioactive pollutants, but to a much lesser degree than from the nuclear processes. Radionuclide emissions by 2000 may be up ninefold over 1975. But the potential level of exposure to the public would be far below that from natural sources, medical uses, and other technology-caused emissions, such as plane travel.

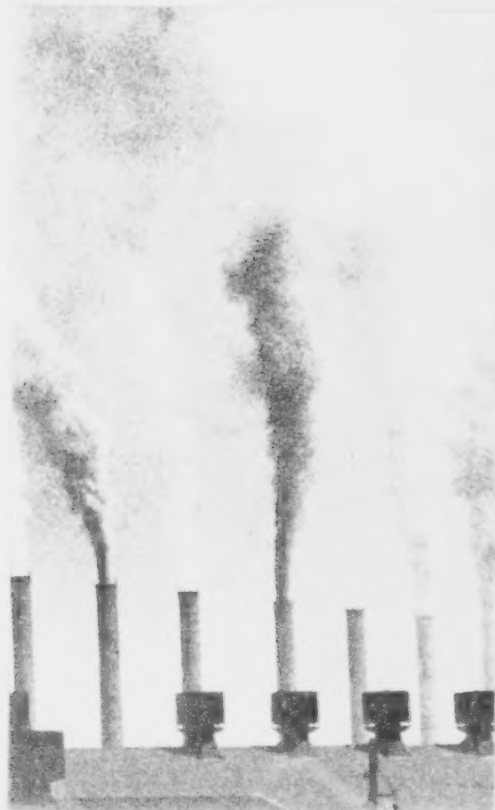
The United States need not make premature decisions about the use of new technologies as long as further information about their environmental and health characteristics is developed along with the technology. The same is true for their technical and economic feasibilities. That's why it is necessary to develop a number of options. We would have the flexibility to turn from one technology to another or from one source to another if one or more supply options proved to be unacceptably hazardous. It is the job of my Office of Environment to help the country prepare to make those decisions. We do not work alone, either within the Department or within the Federal establishment. It is a cooperative venture. And it is also a very difficult one.

THE ENERGY/SAFETY SCALE

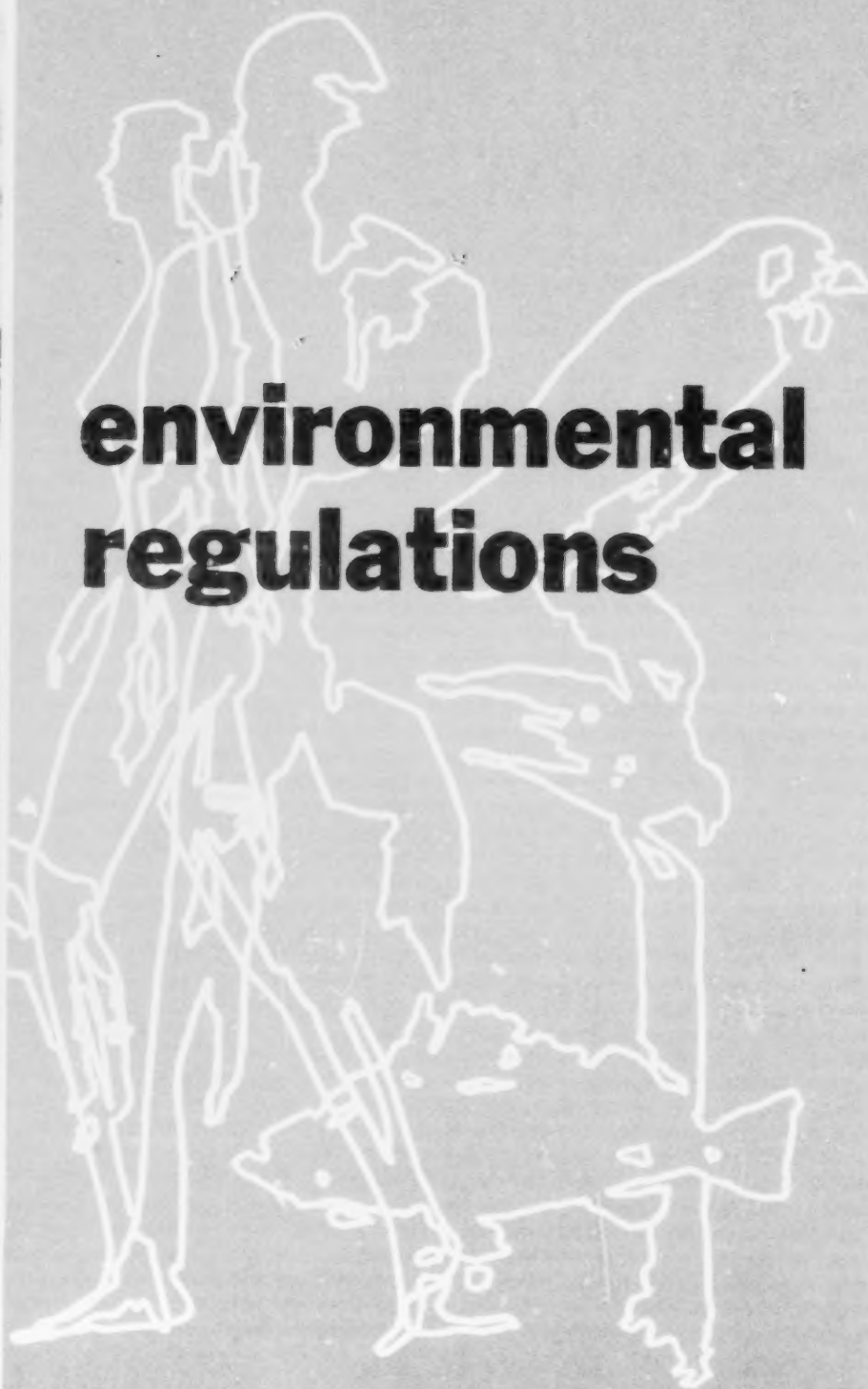
Nevertheless, we must all work toward solutions. We must balance our energy requirements with health and safety demands. We can ignore neither side of the scale. Our children and grandchildren depend upon us. We have got to use common sense.



session 2



environmental regulations





Walter C. Barber

ENVIRONMENTAL REGULATIONS: AIR

Walter C. Barber, Jr.

Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency

A LONG DEBATE

The Clean Air Act amendments of 1977 concluded a long debate between environmentalists and industry over the adequacy of our new source performance standard for steam electric power plants. At that time there was evidence that we were going to burn a lot more coal and we needed to again look at the question of whether low sulfur coal should be treated to nearly the same degree as high sulfur coal. There was substantial concern that the eastern coal markets would be displaced by imported low sulfur coal—to the eastern markets, imported means bringing it in from the west—and there was substantial concern in the environmentally oriented community that doing less than the best in the west would result in increased emissions, feasibility impairment, and general degradation of air quality in and around the parks.

That the Act required EPA to review the standard clearly indicated that Congress felt the standard of 1.2 pounds per million BTU's was inadequate; Congress remanded the standard to EPA to strike another energy environment and economic balance for steam electric power plants, giving particular consideration to the question of the degree of control required for low sulfur coal-fired power plants. We did that. It took a long time. Most of you probably followed the saga in the press and in the Federal Register. We promulgated that rule and it appeared in the Federal Register.

SETTING THE STANDARD

In setting the standard, our approach was to look at both individual plants and model plants. We were also concerned about what the environmental impacts relating to individual plants were. At the same time, we needed to take a careful look at what a more stringent standard might do to the overall energy economy; what we were going to do to both existing and new plants; and what the net effect on the environment, the economy, and the coal markets would be. That is the exercise that took so long and that has been debated at some length. The final standard calls for essentially full control of all coal-fired power plants. It provides an opportunity for the sulfur oxide emissions to meet a slightly less stringent standard in the event that the coal is low enough in sulfur and it allows new technologies that have substantial economic and energy benefits to penetrate the marketplace.

SO₂ EMISSIONS REDUCED

Total coal production in the United States is currently 650 million tons. By 1995 that amount will increase two and a half to three times. Had we not changed the standards, that is had we left it at 1.2 pounds per million BTU, we would have had from the power plants subject to the standard—and those are the power plants that will come on line between late 1983 and 1984 along with a set of plants that will come on line between 1984 and 1995—7 million tons of SO₂ emissions in 1995. So, basically, the revision to the standard will reduce by more than 50 percent the SO₂ emissions associated with the subset of plants that are subject to this standard.

From power plants, we now have about 19 million tons of SO₂ emissions nationwide. Had we not changed the standard, we would have almost 24 million tons in 1995. The way we promulgated the change in the standard, we expect to have about 20-1/2 million tons in 1995. Three million tons is the difference between what we would have under the old standard and what we would have under the new. We had a difference of about 3.9 million tons between the old standard and the new one, but we won't see that 3.9-million ton difference because as we make power plants more expensive, and it is obvious that we are making them more expensive, people tend to build fewer new ones and to use the old ones. Old power plants are substantially dirtier than new power plants. The average coal-fired power plant in existence now emits about 80 pounds of SO₂ per ton of coal burned. The power plants that we are talking about are going to emit about 12 pounds of SO₂ per ton of coal burned so we are going to get a substantial shift in the SO₂ emissions from power plants.

Most of what I am going to talk about today has to do with SO₂. There is a pretty vigorous particulate standard that was promulgated—0.03 per million BTU, which is about a 70-percent reduction from the current standard and which will require aggressive application of either precipitators or baghouses on these power plants. There is a marginal increase in stringency in the NO_x emission limit from the current 0.7, down to the 0.5 or 0.6 range.

FULL CONTROL VS PARTIAL CONTROL

The current standard shows about 23.7 million tons, and the revised standard about 20.5 million. This breakdown is the total national emissions. There are two alternatives: the so-called full control alternative that was favored by the environmentally oriented community and the partial control or 33-percent alternative recommended to us by the Department of Energy, which was similar to the recommendation provided by the utilities. The most stringent alternative results in more emissions than the alternative we have adopted, which may be counterintuitive, but that is the way it works. That is particularly significant in the east where there is a several hundred-thousand-ton difference. The reason is simply that existing power plants are used more as the standard becomes more stringent and the full control across-the-board alternative is substantially more expensive. As a result, it encourages people to run coal plants that emit 80 pounds of SO₂ per ton rather than build coal plants that emit 12 pounds of SO₂ per ton.

Congress directed us not to create an unreasonable incentive to bring low sulfur coal into the East thereby displacing eastern coal markets. Our analyses showed that, if we didn't change our standard, by 1995 we would have about 122 million tons of coal coming east of the Mississippi. Under the revised standard we would have 70 million tons, or about 50 million tons less. Congress did not want us to disrupt the coal markets. Under the present standard, Appalachia produces 400 million tons and the Midwest, 150 million tons. This production increases with our revised standard.

NEGATIVE ASPECT OF REVISING STANDARD

Even if we retained the current standard of 1.2 pounds per million BTU, we are going to have 1.4 million barrels a day of oil being burned in power plants in 1995, which means we will be putting just as much oil into power plants in 1995 as we are putting into power plants now. Making the standard more stringent unfortunately encourages people to put more oil into power plants; under the most stringent alternative it would be 400,000 barrels a day; under the alternative we have selected it would be about 200,000 barrels a day. That is one of the negative aspects of revising the standard.

The plants that we have now or that are being constructed are subject to the current 1.2-pound NSPS. There will be between 15 and 16 million tons a year of SO₂

emissions in 1995; they dominate the system. As we make the standard more stringent we can bring 7.5 million tons down to 3.1 million tons. None of the alternative standards brought that number any lower than the finally selected one at 3.1 million tons. If we don't change the standard, the emissions from all power plants, would be about the same as with the revised standard. Once again, this is because making things more expensive under the full control option encourages people to use the SIP/NSPS plants more.

ECONOMIC IMPACTS

We have used four or five indicators of economic impacts, one being the average, monthly residential bills in 1995. If we don't change the standard they are going to be \$53; if we do change the standard they are going to go up 2% percent which is about \$1.30 a month. Indirect consumer impacts, the increased cost of purchases, are going to be about the same, another \$1.30. To the average residence, in 1995 this standard is going to cost \$2.50 over an electric bill that now runs about \$53 direct, and the \$53, which is in current dollars, compares with a current average residential bill of \$26. So, for reasons that don't have a lot to do with this standard, everybody's electric bill is going to double. That is because we are going to use more electricity for more and different kinds of appliances and labor, transportation, and fuel rates are going to go up, as well as construction rates, at a level faster than the rate of general inflation.

Another indicator is the total increased utility capital requirement. There was concern that this standard would make it difficult for utilities to find money to operate. We looked fairly carefully at the availability of capital to build new power plants and found about \$770 billion between now and 1995 had to be spent on new capital plants. This standard basically adds between zero and \$10 billion to that. The total capital change obviously reflects decisions not to build new power plants. The capital cost of the control equipment that we are talking about would be in the tens of billions of dollars, in the 1995 timeframe, about \$30 billion.

INCREMENTAL ANNUALIZED COST

Incremental annualized cost was an indicator as to how much of the total national electric bill this standard was going to cost; the total national electric bill in 1995 is estimated at \$175 billion. This standard increases it somewhere between \$3 and \$4 billion, depending on the choice made. This makes the decision process difficult because, on one side, the most stringent alternative, the full control, is only \$4% billion more than the \$175 billion we already have to collect. On the other side, it is \$1% billion more than the alternative that we selected, and \$1 billion is still a lot of money even when compared with \$100 billion.

The present value of incremental utility revenue requirements is just that—all of the costs accrued to the utility through the useful life of those plants brought back to the present ends up being about \$30 billion and the incremental cost of SO₂ is about \$1,000 a ton. Under the most stringent standard it got up to \$1,400 a ton. None of them got under \$1,000 a ton. So, compared with our current several hundred dollars a ton for SO₂ control costs, this one is not cheap.

EMISSION RATE CEILING

A fair amount of debate in the final stages of this standard surrounded the level of the maximum emission rate. We looked at the ceiling question. The press was interested because there were coal miners who felt that we were prejudiced against the very high sulfur coals prevalent in the northern Appalachian and midwestern area. It turns out that the way we have structured the standard and the way coal reserves are deployed around the country, there isn't very much of that coal likely to burn relative to the other available coals. We therefore looked at very low ceilings, as low as 0.6 pounds per million BTU averaged monthly and decided to consider making every plant emit no more than 0.6 pound per million BTU. That turned out to be a fairly cost effective way to get SO₂ out of the air, and the economists reveled in the idea of shifting our coal market from the high sulfur coals to the low sulfur coals. One risk when using national-scale economic models is that they do things which don't have a lot to do with reality.

When pushed down to 0.6, all that is done is to take people who are now mining 0.8- and 1.0-pound coal and shifting them over to 0.6-pound coal. It is all new mines. Instead of mining that coal we will mine 0.4-, 0.5-, and 0.6-pound coal. We have two to three hundred years worth of coal. Let us just shift our emphasis. But it turns out

EFFORT TO STRIKE A FAIR BALANCE

that a lot of people have invested large sums of money to assemble the reserves which they are planning to mine over the next 10 years and not all of those reserves happen to be in the less than 0.6-pound range. It became evident to us that we were going to disrupt coal markets over the next 10 years until this big shift could take place. That didn't seem to be particularly compatible with the effort to shift to coal for our new generating requirements. So that is where we ended up. We ended up with a 1.2-pound ceiling. This is what the roughly 350 power plants will be doing in practice. The way we have structured the standard there is some encouragement for them to get under the 0.6 level. We expect that of the 350 power plants, roughly 278 will be less than 0.6 in terms of average monthly emissions. We expect that about 50 will be between 0.6 and 1 and that about 22, between 1 and 1.2. That is one issue, I think, that is fairly well developed in the preamble of the regulation and you may come to a clear understanding by reading that.

I would just close by saying that writing rules that are going to affect the energy industry from the environmental perspective has become substantially more complex and more time consuming. We are endeavoring to deal with these monumental problems that are associated with billions of tons of coal, millions of tons of sludge, and billions of dollars to the consumer. We have come a long way since 1972 when we could put a rule like this in the Federal Register with a few marks on the back of an envelope as to cost estimates. I think that this standard represents an effort by the Agency to strike a fair balance. If you look carefully at the numbers in the Federal Register, you will see that we have gotten what is nearly, if not entirely, the environmentally preferable option. We have identified a way to give the utilities enough flexibility so that they can save about a billion dollars a year.





Sverre T. Davis

ENVIRONMENTAL REGULATIONS: WATER

Sverre T. Davis

Office of Water Planning and Standards
U.S. Environmental Protection Agency

In industry, water regulations traditionally have not had the cost impact and generated the controversy that air regulations have. The problems that air regulations have to deal with, either directly or indirectly, run head on into energy industries or energy policy, which is not the case with water regulations. This is changing somewhat because the relative importance of energy is increasing in the water regulations. These increases can be explained, first, by the fact that an energy-cost increase will make the energy factor more important simply by increasing the overall costs of those regulations and, second, by the fact that the phenomenon is exacerbated somewhat because the second round of technology requirements, primarily those for industry, are expected to be much more energy intensive than the first round of standards. There is a much greater reliance, for example, on reuse and recycle technologies, and these, in general, require greater amounts of energy.

THREE GROUPS OF WORK

The work we are doing in water as it relates to energy can be put into three groups. The first contains cases of direct regulation of energy that currently is a major industrial factor in the energy field, examples being the steam electric utilities industry, the petroleum refining industry, and the coal mining industry. The second group contains the emerging energy technologies which, by definition, are not now regulated, but which we are working on so that when they finally become commercial, regulations for water pollution will already be understood by the industry. The third group contains those cases where we regulate industries that are not energy industries but, because they are in the process of complying with water regulations, would have energy requirements and an energy impact.

PRIMARY FOCUS

I will focus only on the first two groups. Although there are greater energy impacts on the nonenergy industries, I think the energy factor, in most cases, is still not the constraining factor but that overall cost and economic trade offs are. But compared with the cost of air control regulations, the energy impacts in those industries are relatively minor. The commercial energy industries in this country and the ones that we regulate in the water pollution programs are the primary ones that we

worry about right now. They are steam electric utilities, petroleum refining, coal mining, and ore mining. I will comment mainly on the steam electric and petroleum, the two industries in which we have progressed the most in developing our current round of regulations.

The regulatory work in the Water Act generally lags behind the Clean Air Act by 1 to 2 years because the Water Act itself was passed at a somewhat later date. The whole regulatory effort in water, going back to its statutory basis, is lagging somewhat behind the air program. My comments will therefore be dealing with regulations that are still 6 months to a year away.

FOCUS ON TOXIC POLLUTANTS

In the petroleum refining and steam electric utility industries, our focus in this round of regulations has primarily been upon toxic pollutants. In the 21 industries we are looking at, which include these two industries, we have found some measure of toxic pollutants in practically every industry. We are setting aside industries that do not show substantial amounts of toxics or that have 1983 standards that already control them substantially and we are focusing on only the remaining industries. Even within those industries, for example within the petroleum refining industry, we have found in the untreated waste streams about 6 or 7 of the 129 pollutants we are focusing on. Of those 129, about 41 are found even in the treated waste waters after what we call best practical technology of the 1977 requirements. Of that 41, we, nevertheless, will focus on a still much smaller number for regulatory purposes, partly because all of them are not found consistently enough or in high enough quantities to worry about and partly because from a practical point of view it doesn't make sense to attempt to regulate every pollutant.

PETROLEUM REFINING INDUSTRY

Basically, there are three regulatory approaches we are looking at in the petroleum refining industry. The first is the reuse and recycle technologies that are well established within this industry. Practically all industries recycle to one degree or another as a result of the 1977 requirements. The 1984 best available technology (BAT) requirements will probably include some degree of additional recycling and reuse as part of the overall regulatory structure. The second regulatory approach would be the end-of-pipe treatment and the primary one being studied is powdered activated carbon. There is a substantial difference in the cost of powdered activated carbon and granular type activated carbon. A rough estimate of what it would cost annually, including output and maintenance cost, for the entire industry to install and operate powdered activated carbon is \$66 million a year, which is relatively small compared with what we are spending for air pollution control. The cost for granular activated carbon would be approximately five times that amount, or about \$360 million a year. For a very minor sacrifice in pollutant control, there is about a fivefold savings in cost by using powdered activated carbon. The third regulatory approach is no-discharge of waste water pollutants which is simply an extension of the reuse and recycle approach. It has been demonstrated in the petroleum refining industry and it is most commonly found in the western states where water shortages have forced these industries to develop much more advanced waste-water management practices. We currently know of about 50 or 55 refineries that now practice this.

STEAM ELECTRIC UTILITIES

Like the petroleum refining industry, the steam electric utility industry is, to an even greater extent, a very high volume industry. This is true not only for thermal waste streams but also for the so-called chemical waste streams, which may be relatively small within this industry but compared with many other industries are still very large. We find that the pollutant problem is one of quantity, as opposed to concentration level. In many cases the concentrations are extremely low. However, because the pollutants are often heavy metals or are very persistent in the environment, their concentrations are very high in volume and can still be of concern.

Within the steam electric utilities industry we have focused our attention primarily on cooling water waste and ash transport streams. By far the largest in volume is the cooling water waste stream in which the concentration levels of pollutants are extremely low. Rather than focusing on individual organic toxics, we will be primarily focusing on residual chlorine and the concern about chlorine itself being toxic, at least in the higher concentrations. Residual chlorine greatly increases the probability of chlorinated hydrocarbons being created in the waste streams before discharged.

Probably the more controversial and the more expensive in terms of regulations that might finally be proposed and promulgated are ash transport streams. They come in two or three different forms. We focus mainly on fly ash from electric type precipitators and on bottom ash. Although we are not focusing on it very much, there is a third waste stream soon to be generated, at least in an official sense. It is ash that results from the scrubber process. Depending on the kind of waste stream, we are considering alternative chemical additives for dealing with some of the problems that we find in cooling water streams. Petroleum refining reliance upon water reuse from recycle is a primary alternative mode of ash transport. End-of-pipe treatment is most applicable for ash transport but the extremely high volume of the cooling water stream makes it a much more difficult option to consider from an economic point of view.

Last, but not least, management practices themselves are being studied. The ways in which plants are operated can greatly alter and reduce potential environmental impacts from, for instance, the cooling water stream. This is an option we will be trying to fit into the whole regulatory package. It is a much more effective and a much cheaper approach than trying to do end-of-pipe treatment.

Because of the large size of the plants involved in the utilities industries, the volume of the waste streams, and the large numbers of plants, it is easy to conceive a price tag for water regulations and control in excess of \$1 billion.

EMERGING TECHNOLOGIES

Although none of our regulatory efforts at this point include the emerging technologies, there is a great deal of effort in terms of actual dollars and man-years of effort under way in my office. There is even greater effort in other parts of EPA and in other agencies, such as the Department of Energy and the Department of Interior. Our objective is to try to get ahead of a power curve in the emerging technologies and to determine in advance what types of pollutants can be generated, how serious they might be, and what type of technology or management steps can be taken to deal with them. We also must try to lay these out and make them well-known to the industry before they reach the commercial stage so that the proper kinds of controls can be included in the design. We have had very bitter experiences, in some cases, with the earlier regulatory effort; it isn't possible many times to adequately deal with the toxic problem and other pollutant problems in a retrofit situation and even when we can deal with them, it is at great expense and with great controversy.

OIL SHALE

Three technologies that I will discuss next are oil shale, coal gasification and liquefaction, and geothermal which are only in the development stage. Based on what we have done so far, mainly work in research and development, there could be significant concentrations of toxic pollutants generated from oil shale. One advantage of looking at this early is that there are a number of options for dealing with oil shale, including studies that indicate feasibility of zero discharge of waste water pollutants. Industry is considering zero discharge types of requirements in designs in oil shale technologies. A big factor is that a tax credit is being considered in Congress for oil produced from oil shale which would provide a substantial incentive for this technology to be accelerated commercially.

We are also exploring coal gasification and liquefaction for toxic pollutants. We have found, in some cases, inorganics from the coal itself, phenolic compounds, and some aromatics. It is early to say what can be done, but these are pollutants that we have been able to deal with in other industries. We are starting to do feasibility work on bench scale plants and, we hope in the near future, to start doing research and development on commercial power scale facilities.

GEOTHERMAL

We are not focusing very hard on the entire toxics list in the case of geothermal. There are a relatively small number of pollutants that we would be concerned about but I can't give you any quantitative sense of how great a problem this would be. It is simply the list we would expect. It includes boron, bromine, ammonia, arsenic and mercury. There are numerous ways of dealing with them, including treatment technologies and process approaches which we will try to explore as we learn more about the exact quantities of pollutants generated.



Steffen Plehn

IMPACT OF THE RESOURCE CONSERVATION AND RECOVERY ACT ON UTILITY WASTE

Steffen Plehn
Office of Solid Waste
U.S. Environmental Protection Agency

The Resource Conservation Recovery Act (RCRA), which was passed in 1976, has two goals: to protect the public health and the environment from the improper disposal of solid waste and to encourage and facilitate the conservation and recovery of resources from solid waste. Under this Act, EPA has essentially three programs. Taking them in reverse order, there is a program to encourage the recovery of energy and materials primarily from the municipal solid waste stream. This program intersects with many utilities with regard to the use of solid waste, or fuel derived from solid waste, for the production of energy. Statistically the energy value of municipal solid waste in standard metropolitan areas is equivalent to about 400,000 barrels of oil a day. In Europe, and particularly in Japan, that waste is turned into steam and then into electricity, or used directly as steam. We are well behind those countries but are coming along. The technologies we now have and our most difficult problems are those that relate to institutional constraints for getting communities organized to procure and operate those plants, but we have a program to accomplish this.

REGULATION FOR SAFE DISPOSAL

Congress set up two programs for the safe disposal of wastes. One is under subtitle C of the RCRA and the other under subtitle D. For regulation of hazardous wastes, Congress called for a cradle-to-grave Federal program that they hoped all states would adopt and implement. For all other solid wastes, Congress determined that the primary responsibility should rest, as it now does, with state and local governments and that the Federal Government's role should be limited to developing criteria that would define sound landfill disposal. The states would then develop regulatory programs consistent with the Federal criteria.

We proposed a regulation about a year ago which we expect to promulgate in July. The regulation will establish performance requirements, will ensure that land disposal will not pollute ground water, surface water, or add to air pollution and that land disposal sites are not placed in environmentally sensitive areas which are flood plains, wet lands, et cetera.

CRADLE-TO-GRAVE PROGRAM

CHARACTERISTICS OF HAZARDOUSNESS

SPECIAL WASTES

Under subtitle C of RCRA, hazardous waste is defined as solid waste that may cause or contribute to an increase in serious illness or mortality because of its quantity; concentration; or physical, chemical, or infectious characteristics or may pose a substantial present or potential hazard to human health or to the environment when improperly treated, stored, transported, disposed of, or otherwise managed.

As I said earlier, the Act provided for a cradle-to-grave regulatory program for wastes. Congress determined that wastes are so mobile that they must be brought into a regulatory system at the time they are created and must be regulated until the time they are finally disposed of. We are required to promulgate seven regulations which (1) define what a hazardous waste is; (2) establish the responsibilities of generators of wastes; (3) establish the responsibilities of transporters of wastes; (4) set design and operating standards for facilities at which wastes are either treated, disposed of, or stored; (5) define a permitting system for those facilities; (6) establish the rules under which we would authorize states to run the program; and, finally, (7) define a regulation requiring notification by generators of wastes as soon as the regulations are promulgated.

The Act provides two specific means by which a hazardous waste can be identified. One is simple tests that test for four characteristics of hazardousness. These are whether the waste is (1) ignitable, (2) corrosive, (3) reactive, or (4) toxic. Feeling that we needed more help from the world, we also proposed two additional characteristics for public comment: (1) radioactivity and (2) organic toxicity or more specifically mutagenicity, bioaccumulation, and other elements relating to organic toxicity. The second means by which a waste can be determined to be hazardous is if, based on available evidence, the administrator determines that it is.

In our proposed regulation we listed about 150 waste streams or particular wastes which we believe the evidence indicates are hazardous. Many of those are in the area of organic toxicity because our characteristic for determining organic toxicity is not sufficiently well developed and validated to serve as a keystone for this regulatory program.

As we were developing this hazardous wastes regulation, we realized that some of the high volume wastes that are produced in the process of electricity generation could potentially be hazardous. We concluded that there was a possibility that when tested, fly ash and bottom ash could possibly be toxic, corrosive, or reactive. Because of trace metal concentrations in sludge, scrubber sludge could potentially be toxic. We also concluded that it would not be appropriate to apply the range of design and operating standards which are now developed to ensure that the Love Canals of the future do not occur to large volume and comparatively low hazard wastes.

We, therefore, proposed a special classification for handling those wastes which we call special wastes. Coal utility and other steam power plant wastes, coal mining and milling wastes, and uranium mining wastes are specifically identified as special wastes. Such wastes would be exempt from financial responsibility requirements and treatment, storage, and disposal requirements that would be applied to other hazardous wastes. We need to know a lot more than we now know about how to properly manage special wastes.

If wastes violate any of these characteristics, they would then be subject to a very limited number of requirements: waste analysis, the siting of new sites, security, record keeping, and closure and monitoring.

Industry was extremely concerned about what proportion of these wastes might, in fact, tilt against these characteristics. Since December, industry and we have been doing a lot of testing to see what the score is. At TVA, 10 samples of fly ash and bottom ash were tested for characteristics of hazardousness. In nine of those, neither the fly ash nor the bottom ash flunked and the 10th sample appears not to have either, but it needs more work. If those particular data are an indicator, fly ash and bottom ash would be affected by this regulation as it was proposed.

OTHER FEDERAL STATUTES

Working in conjunction with EPA's Office of Research and Development, we have begun to accumulate data for analysis to determine management standards for the protection of the environment and the public health. We are currently in the process of selecting sites for this analysis. We will then conduct full field investigations, including monitoring of surface water, ground water, and the air at about 10 mining and 16 utility sites. We expect that by 1982 the results of these studies will put us in a position to propose regulations for the management of wastes. An amendment to RCRA proposed by Senator Huddleston says that EPA would not proceed under subtitle C of RCRA with any regulation of these utility wastes until the studies, which I have described, are complete. At that time we will decide whether to have regulations. Whether that amendment will survive, I don't know, although my expectation is that it will.

Two other federal statutes affect the management of solid waste. One is the Surface Mining Control and Reclamation Act under the Department of Interior which regulates surface mining and also waste disposed on the surface as the result of underground mining. We and the Department of Interior's Office of Surface Mining have overlapping authority for the regulation of those wastes. We have been working with the Department of Interior to delegate our responsibilities under RCRA to the Office of Surface Mining. We find their disposal criteria satisfactory except that they do not require ground water monitoring of all disposal sites. We believe that these sites should be monitored so that action can be taken to deal with problems before an aquifer is polluted.

Another Act of interest is the Uranium Mill Tailings Radiation Control Act which Congress passed last fall. This includes the disposal of uranium mill tailings, both radiological and nonradiological hazards. The law says that EPA is to write the regulations under this Act, and that the Nuclear Regulatory Commission is to enforce them through their permitting system. The statutory dates for these regulations are November 1979 for inactive sites and May 1980 for active sites.

It is important to understand that the Resource Conservation and Recovery Act addresses, almost solely, the management of hazardous wastes from the time of its promulgation. The Act mandated the establishment in 1976 of a regulatory structure that would, over time, regulate all waste disposal. We have just recently come to the realization that the problem of past inadequate disposal of hazardous wastes is of an order of magnitude far greater than anyone had understood. We had very limited legislative authority and virtually no resources with which to address this problem. We are therefore reorienting and augmenting our efforts.

AGGRESSIVE AND FORCEFUL ENFORCEMENT

There are now more than 100 people working on the problem of inactive and abandoned sites, with 144 cases under investigation. Seven imminent hazard cases have been filed under RCRA and other EPA authority. Where we can make a case and locate a responsible party, we are proceeding with enforcement aggressively and forcefully. We look forward to the proposal of legislation to establish what is colloquially referred to as the superfund, which would integrate our responses to inactive and abandoned sites with our Spills Response Program for oil and hazardous materials under Section 311 of the Clean Water Act and, also, provide resources to contain those sites for which there is no evident and solvent owner and which pose a threat to public health.

questions & answers

Leon Green, Jr.
General Atomic Company

Dr. Margaret E. Hamilton
Delaware Chapter, National Audubon Society

Howard Hagler
Resource Planning Associates, Inc.

Robert Roach
National Audubon Society

Jean B. Cornelius
Avon Lake League of Women Voters

Robert C. Gabler, Jr.
U.S. Bureau of Mines

Mark Gottlieb
Office of Radiation Programs
U.S. Environmental Protection Agency

John A. L. Campbell
Peabody Coal Company

Benjamin Linsky, P.E.
West Virginia University

Alex Wormser
Wormser Engineering

QUESTION

Will coal ash be regarded as hazardous because of its radioactivity?

RESPONSE: Mr. Steffen Plehn (EPA)

Yes. We have announced in an advance notice of proposed rule-making our current thinking as to how to approach radioactivity as a hazard, not only with reference to coal but elsewhere. We have received comment on that and will be working to improve and finalize our thinking. I expect that in 1980 or early 1981 we will propose a characteristic and move toward its inclusion in the hazardous wastes regulatory program.

QUESTION

The Department of Energy is committed to an educational conservation program, but you are anticipating an increase in energy consumption and a doubling of the average electric bill. How can these two viewpoints be reconciled?

RESPONSE: Mr. Walter C. Barber, Jr. (EPA)

Doubling the average electric bill does not mean the same as using twice as much electricity. There is a growth rate in electrical demand nationwide, some of it associated with increased use by individual consumers and some of it associated with general growth in the economy. It is not the sole contribution to increased cost; that has to do also with increased fuel, transportation, and labor costs. The Department of Energy and the Environmental Protection Agency worked together to develop these projections. The total growth rate used as the basis of the Department of Energy's projection is about 2 percent per year.

QUESTION

Your comparison of the 1975 and the 1995 coal production showed some rather startling increases in regional projections, particularly in the Midwest and the northern Great Plains. How realistic are those projections, and how do they relate to the rest of the information you displayed?

RESPONSE: Mr. Barber

The question is one of how we are going to get the coal. An estimate has been made of the country's total electrical demand, a demand which must be met by some means. Because of limitations on nuclear power generating construction, we project that most of the demand will have to be met by coal-fired power plants. The model used to estimate coal is an economic model, which says that those two areas of the country are going to a) experience increased demand, and b) have coal available at a reasonable price. Whether the coal industry can produce enough coal is another question, but it is consistent with the estimates the Department of Energy has been developing.

QUESTION

What plans are being made for public or community participation in the siting of storage facilities for toxic or hazardous substances?

RESPONSE: Mr. Plehn

The problem of siting is the most difficult problem that will have to be solved if we are to achieve safe hazardous-waste management. Everybody insists that wastes be disposed of properly, but nobody wants the disposal to be within his own range. Public opposition is a very difficult problem. In an effort to involve citizens

in learning about and participating in the siting of such storage facilities, we have started a program called waste alert. We are conducting a series of regional conferences, to be followed by state conferences. Douglas Costle, Administrator of the U.S. Environmental Protection Agency, appeared before the National Governors' Association last February to bring the disposal problem to their attention. He said that it is EPA's strong belief that each state must develop procedures consistent with its own constitution and laws to address the siting problem systematically: to ensure that all the technical requirements for candidate sites are identified, to provide for full public participation in the evaluation of those sites, and also to assist in the final selection of sites. Although a number of states are moving in this direction it still remains our most difficult problem.

QUESTION

A headline this morning announced that the Environmental Protection Agency had decontrolled all electric utilities in Ohio. They will not be required to have scrubbers, and they will be allowed to burn high-sulfur coal. Those who have fought to force the utilities to get scrubbers were banking on the backing of EPA. What are the reasons for eliminating the standards?

RESPONSE: Mr. Barber

The Federal Government, in the absence of an Ohio State Implementation Plan, adopted emission limits for essentially all the major power plants in Ohio. We are going to take another look at two power plants owned by Cleveland Electrical Illuminating. Those two plants were modelled using state-of-the-art techniques at that time. We have decided that the models used when we set those initial emission limits some years ago were inappropriately applied. Rather than force those power plants into compliance with potentially, and perhaps substantially, erroneous emission limits, we are going to reevaluate the air quality data associated with them and set a revised emission limit before they buy scrubbers. We have seen a fairly clear error in the application of the modelling techniques to these two plants in particular, so we are going to maintain the status quo in those plants until the modelling is completed.

COMMENT

We have been studying recovery of ash samples for various metals from approximately 11 plants. All but one of these samples arrived in plastic containers. That one arrived in a tin-plated, steel can. Within about 3 weeks, the wet bottom ash ate completely through the can, meaning that it was clearly a corrosive material and that it definitely would fit the definition of a hazardous waste. The effects of the other samples are not known, because they were in plastic, but some of the wet ash samples are quite corrosive because they are very caustic.

QUESTION

In regard to policy concerning control of radioactive substances, to what extent does the Resource Conservation and Recovery Act (RCRA) allow development of control technologies to deal with this, and to what extent is it EPA's responsibility to develop these technologies? Or is this more the responsibility of the private sector?

RESPONSE: Mr. Plehn

The basic orientation of RCRA is the establishment and effective implementation of a regulatory structure. There is ample authority for EPA to work on control technologies for any particular waste. The degree to which EPA will do that work depends heavily on the resources available. Up to now, the work done in the Office of Solid Waste has been very limited in that area.

RESPONSE: Dr. Steven R. Reznick (EPA)

The Office of Energy, Minerals and Industry is working on the disposal of uranium-mining operations. Once the first concentration step occurs, however, the Office of Research and Development is no longer involved. We aren't doing anything about developing radiation protective methods.

QUESTION

There seems to be a question whether the coal industry can meet the energy needs. The problem right now is actually one of over-capacity with estimates of approximately 100 million to 150 million tons over-capacity. The industry is closing down mines; we can't sell coal because of the soft market, and this in a time of great national concern about the energy crisis. The reasons for this are hard to pin down, but one major reason is air pollution regulations. My company had to close a very large mine complex in Ohio because of air pollution problems. There is concern in the industry about the role that health effects will play in setting new sulfur standards. As there is very little information about this aspect, would you tell us how large a role you expect health effects to play?

RESPONSE: Mr. Barber

The New Source Performance Standard is a technology-based standard, the intent of which is to ensure that as we put in new capital stock over the next 50 years we do it cleanly and obviate the need to make massive retrofits of our existing plants. Certainly health effects data are sparse. There are two disparate opinions resulting from that: one opinion says, when in doubt do nothing; another opinion says, under conditions of uncertainty take some prudent action. Other heads than mine will decide on the degree of stringency to be applied under conditions of uncertainty, but for every one who thinks we are proceeding at too aggressive a pace on sulfur oxide issues, there is one who believes we are proceeding at too lax a pace.

QUESTION

Although it is expensive from an energy viewpoint, as we have enough coal, isn't expanded use of dry cooling a feasible way to get rid of some of the troublesome chemicals and thermal water pollution, particularly in the East and Midwest, where water is in increasingly short supply?

RESPONSE: Dr. Reznick

The Office of Research and Development has done an extensive study of how much water is necessary to produce energy, either electricity or synthetic fuels, and they have looked with great care at alternatives to wet cooling. A combination of wet and dry cooling is quite an attractive alternative, particularly in the northern areas of Montana and the Dakotas and in West Virginia. Although there is a cost penalty, it is not too far out of range. In areas where water has to be transported a long distance to a plant, building the plant at the coal and deciding to go wet/dry is the economic choice. To go to dry by itself and eliminate all cooling water, either for electricity generation or for some of the other processes in these energy technologies that are coming along, going to total dry cooling, eliminating all cooling water for electricity generation or for some of the newer technologies, is an extremely expensive proposition though it can be done. Two plants are using it today but at great expense, and it actually changes the price of electricity substantially. The normal price for irrigation water is between \$10 and \$12 per acre foot, the volume of water that would cover an acre in area. Energy would pay between \$100 and \$200 per acre foot of water per year, raising the production cost of electricity by about 2 percent. You would cut that in half, however, for delivered electricity, so there is about a 1 percent increase for zero water being put into the plant and going out, except for the small amount of feed water.

RESPONSE: Mr. Swep T. Davis (EPA)

The Office of Water Planning Standards and Regulations is basically setting nationwide standards. Often we come across a case where something unique has been done, that is feasible only because of a unique set of circumstances. Sometimes that can be built into the national standard, but usually it is very difficult to do so. Also, our primary focus right now is on toxic chemicals. Consequently, although there are some toxic chemicals associated with the thermal stream, they are relatively minor compared to what is contained in other industrial waste streams, and we are not focusing on them. It is true that water shortages exist all across the country, but the primary purpose in setting regulations is not to conserve water; the primary focus is on toxic chemicals. We would prefer industry response in the form of technology solutions that have secondary effects of benefit for conserving water and other raw materials. Our role is not to leap ahead of the normal economic process and drive it solely for water conservation purposes.

QUESTION

Does the sulfur that can be removed from coal by a cleaning process at a mine subtract directly from the sulfur that has to be removed at the point of use, and is that true for industry as well as for electric utility application?

RESPONSE: Mr. Barber

The standard applies only to electric utilities, and the percentage of removal is an overall percentage from the mine to the stacks. The sulfur, therefore, can be removed anywhere along the way with credit. The law requires that we set a similar standard for industrial boilers, and we expect to propose such a standard in the summer or fall of 1980.

QUESTION

A special waste category for fly ash is now being proposed for industrial waste. Is that likely to be applied to industrial boiler waste as well?

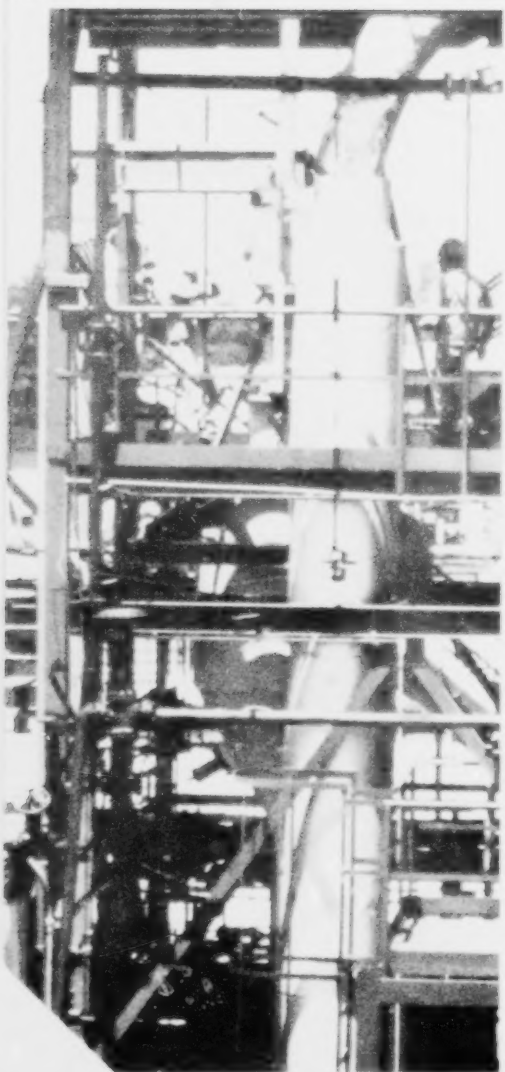
RESPONSE: Mr. Plehn

As it is proposed, it is expected to apply to both industrial waste and industrial boiler waste.



session 3

control technology





Michael A. Maxwell

SULFUR OXIDES CONTROL: FLUE GAS DESULFURIZATION

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EMISSIONS PROBLEM

Mr. Maxwell:

One of the Nation's major energy-related environmental problems concerns the need to control sulfur dioxide (SO_2) emissions from stationary fuel combustion sources. Recent EPA estimates place SO_x emissions at about 26 to 30 million metric tons per year(1). Most SO_x emissions come from a relatively small variety of sources. About 80 percent of all emissions are from stationary source fuel combustion and about two-thirds of all emissions are from the electric utility industry. The remaining 20 percent can be primarily attributed to a few industrial processes: metals smelting and refining, petroleum refining, minerals products processing, and chemicals manufacturing. Approximately 60 percent of the industrial emissions are attributable to the metals industries with the remainder being divided somewhat evenly among the other three areas.

REGULATORY FRAMEWORK

The Clean Air Act as amended in 1977 includes a number of provisions relating either directly or indirectly to the emission of sulfur oxides and other pollutants including:

- National ambient air quality standards (NAAQS)
- Performance standards for new or modified stationary sources (NSPS)
- Prevention of significant air quality deterioration in areas cleaner than required by Federal standards (PSD)
- Methods for cleaning up nonattainment areas

The states and municipalities may enact (and some have) regulations that are more stringent than Federal laws and regulations.

NEW SOURCE PERFORMANCE STANDARDS

Federal emission limitations on sulfur dioxide were initially imposed on new fossil fuel-fired steam generators by regulations promulgated on December 23, 1971. These regulations apply to steam generators with a heat input of more than 73 MW (250 million Btu/hr) and for which construction or modification was initiated after August 17, 1971 (the date of proposal of the standards). The regulations limit emissions to 520 ng/J (1.2 lb/million Btu) heat input for solid fuels (e.g., coal) and 340 ng/J (0.8 lb/million Btu) heat input for liquid fuels (e.g., oil). As an example, this limitation requires removal of more than 70 percent of the sulfur dioxide emitted when burning a coal containing 3 percent sulfur and having a heating value of 28,000 J/G (12,000 Btu/lb). These limitations apply to almost all utility boilers and some large industrial boilers.

On June 11, 1979, EPA promulgated revised new source performance standards for new or substantially modified steam generating units (fossil-fueled), having more than 73 MW (250 million Btu/hr) heat input (2). These standards apply to any units for which construction began after September 18, 1978. For other stationary sources, performance standards are to be set by 1982 for all currently unregulated major source categories. The law requires that all major stationary sources use the best available control technology (BACT) to substantially reduce emissions. In the case of coal-fired power plants, the law specifically defines BACT as the best *continuous* emission control available. The use of dispersion methods (such as tall stacks and cutbacks in operation during adverse weather conditions) alone instead of emission reduction technology cannot be used as final compliance measures.

SOLID FUELS

The 1979 revised standards require that emissions for solids or solid derived fuels (except solvent refined coal) be limited to 1.2 pounds of SO₂ per million Btu heat input. A 90-percent reduction is also required for (controlled) emissions between 0.6 and 1.2 pounds of SO₂ per million Btu. When SO₂ emissions are 0.6 pounds per million Btu, a 70-percent to 90-percent reduction in potential emissions is required. A minimum of 70-percent reduction is required even if the (controlled) emissions are less than 0.6. The percent reduction requirement is to be determined on a continuous basis and will be based on a 30-day rolling average. The percent reduction is computed on the basis of overall SO₂ removal, including precombustion treatment and removal of sulfur in the ash.

LIQUID FUELS

For gaseous and liquid fuels (not derived from solid fuels) the limits for SO₂ emissions are 0.8 pounds per million Btu heat input and 90 percent reduction in potential emissions. The reduction requirement does not apply if SO₂ emissions are less than 0.2 pounds of SO₂ per million Btu of heat input.

Anthracite coal is exempt from the percentage reduction requirement but is subject to the maximum emission rate of 1.2 pounds of SO₂ per million Btu of heat input. Other exemptions of various kinds apply to facilities in noncontinental U.S. areas and to resource recovery facilities.

Solvent refined coal (SRC) is subject to the emission limit of 1.2 pounds of SO₂ per million Btu of heat input but requires only an 85-percent removal of SO₂ on a 24-hour per day basis. Commercial SRC demonstration plants will be permitted an 80-percent removal requirement.

PREVENTION OF SIGNIFICANT DETERIORATION

The 1977 amendments specified that sulfur oxides emissions cannot cause an increase over an area's baseline concentration of sulfur oxides where the air is cleaner than the ambient standards. A system of maximum allowable increases has been established with the smallest increase allowed in Class I areas, more in Class II, and the most in Class III; however, no area may exceed the national ambient standards. Mandatory Class I areas include those international parks, national memorial parks, and national wilderness areas greater than 5,000 acres, and national parks of more than 6,000 acres in existence at the time of legislation. All other areas are initially designated Class II. Certain Federal areas may be redesignated Class I; states have the authority to either upgrade other areas to Class I or downgrade them to Class III. However, certain Federal areas of 10,000 acres or more may not be redesignated as Class III. The law does not rule out growth in cleaner than standard areas but requires

major new sources to obtain a preconstruction permit, for which a modeling study must be carried out at the applicant's expense, showing the projected impact of the new source emissions on the air quality of the area.

NONATTAINMENT AREAS

For areas where ambient air quality exceeds the standards, the 1977 amendments provide for an offset policy. Before new sources of emissions are permitted, action must be taken to more than offset the new emissions by reducing existing ones. The objective is to continue reducing a nonattainment area's emissions until standards are achieved but to allow some growth of less polluting industries in the interim.

As mandated by the Clean Air Act, EPA has also promulgated primary and secondary national ambient air quality standards (NAAQS) for SO_2 . Primary standards are designed to protect the public health and secondary standards are meant to protect the public welfare. These standards are given in Table 1. Whereas the NSPS directly limit emissions from certain new sources, the NAAQS indirectly control emissions from

TABLE 1
National Ambient Air Quality Standards for SO_2

	Primary	Secondary
Annual Mean	80 $\mu\text{g}/\text{m}^3$ (0.03 ppm)	—
Maximum 24-hour Concentration*	365 $\mu\text{g}/\text{m}^3$ (0.14 ppm)	—
Maximum 3-hour Concentration*	—	1,300 $\mu\text{g}/\text{m}^3$ (0.5 ppm)

*Not to be exceeded more than once a year.

all sources. To meet the primary standards, the Clean Air Act amendments require each state to adopt (and submit to the EPA Administrator) a State Implementation Plan (SIP) to provide for implementation, maintenance, and enforcement of the primary standard as soon as practicable but not later than 3 years from the date of approval of the SIP. Requirements of the SIP to implement, maintain, and enforce the secondary standard must specify a *reasonable time at which such secondary standard will be attained*. The Clean Air Act amendments of 1977 require review of the criteria documents and NAAQS for sulfur oxides before 1980.

CONTROL OPTIONS

To control SO_x emissions from combustion sources, one can:

- Use low sulfur fuels
- Remove sulfur from the fuel before combustion (coal cleaning and fuel processing)
- Remove sulfur during combustion (fluid bed combustion [FBC])
- Remove sulfur from the flue gases after combustion (flue gas desulfurization [FGD])
- Combinations of the above

LOW SULFUR FUELS

The use of naturally occurring low-sulfur coal is the most straight-forward control option. However, projected production capacity is limited and most low sulfur coal reserves are in the West, far away from Midwestern and Eastern requirements. It has been estimated that low sulfur coal production will supply less than 44 percent of the anticipated demand in 1980. Utilization of low sulfur coal east of the Mississippi leads to substantial transportation costs, yielding overall power production costs comparable to the use of FGD with local high sulfur coals. The recently revised NSPS could essentially eliminate the clean coal option without FGD for new sources since the best low sulfur coal can barely meet the 1971 NSPS.

Techniques for removing sulfur from coal prior to combustion include physical or chemical coal cleaning and the generation of clean synthetic fuels. The former deals with removal of inorganic sulfur-containing matter (e.g., pyrite and sulfate) that is physically associated with the coal. The latter deals with sulfur that is chemically bound within the organic structure of the coal.

PHYSICAL COAL CLEANING

Physical coal cleaning (based on the difference in specific gravities or surface properties of the inorganic matter and the remainder of the coal) has been in use for years. From 20 percent to 80 percent of pyritic sulfur can be removed depending on the coal and techniques used. It has been estimated that less than 13.5 percent of our coal reserves can be physically cleaned to meet present NSPS. Obviously, in complying with more stringent NSPS, physical coal cleaning must be used with FGD or in combination with other controls. Currently, about 50 percent of the domestically consumed coal is physically cleaned to remove mineral matter and mining residue. A portion of the metallurgical grade coals is also cleaned to remove sulfur. Cleaning operations for steam coals have not previously been designed and operated to remove sulfur for compliance with SO₂ emission regulations. The first U.S. steam coal preparation plant designed to remove sulfur for compliance with state and Federal SO₂ emission regulations has been operated at Homer City, Pennsylvania. Two other sulfur removing plants are being planned by the Tennessee Valley Authority (TVA). None of these steam coal plants incorporate the most advanced physical preparation techniques now used in the metallurgical and mineral industries.

CHEMICAL COAL CLEANING

Chemical coal cleaning processes vary substantially because of the different chemical reactions which can be used to remove sulfur and other contaminants from coal. Chemical coal cleaning processes usually entail grinding the coal to small particles and treating these particles with chemical agents at elevated temperatures and pressures. The coal's sulfur is converted to elemental sulfur or sulfur compounds which can be physically removed from the coal structure. Some chemical leaching processes, such as the TRW-Meyers Process, remove only pyritic sulfur. Other less advanced processes, such as that under development by the Department of Energy (DOE), are capable of removing organic and pyritic sulfur. Chemical coal cleaning processes are currently under development at the bench and pilot scales. Optimistically, several chemical processes could be ready for commercial demonstration in 3 to 5 years.

FLUID BED COMBUSTION

Fluid bed combustion processes, both atmospheric and pressurized, remove sulfur from coal during combustion by burning the coal in a fluidized bed of limestone or dolomite. The sulfur in the coal reacts with the bed reagent to form dry calcium sulfate. A portion of the fluid bed is continuously withdrawn to remove the sulfur compounds either by direct disposal or by regeneration of the spent bed material. These processes are currently at the pilot/prototype development stage and may reach commercialization by 1985-1990. This technology may be suitable for new large utility and industrial steam generators. One advantage over the nonregenerable wet scrubbing FGD processes is that FBC processes produce a dry solid waste product rather than a sludge. A process disadvantage is that fluid bed combustors require a much higher consumption of limestone for the same amount of sulfur removal than does a wet limestone FGD system. Consequently, the cost may in fact be higher than that for FGD.

FLUE GAS DESULFURIZATION

Application of FGD systems to large utility steam generators appears to be the major near-term sulfur oxides control strategy. Flue gas desulfurization involves the removal of sulfur oxides from combustion exhaust gases most commonly by chemical reaction with an absorbent in aqueous slurry or solution in an absorption tower. The tower is known as a *scrubber*, thus the common terminology, wet scrubbing. Basically, a scrubber is a device in which gas/liquid contact occurs. Other FGD processes under development remove the sulfur oxides by dry techniques, employing either reagent injection into the boiler/flue gas or the use of spray dryers followed by fabric filters/electrostatic precipitators. Application of FGD to utility boilers has increased dramatically during the 1970's as can be seen in Figure 1. According to the latest EPA survey, 162 utility boilers representing over 71,000 MW of electrical generating capacity will have FGD systems by the late 1980's (3). A summary of the current status of these systems is given in Table 2. As has been the case since the first U.S. FGD systems were installed in the late 1950's, the ordering trend continues to heavily favor wet lime/limestone systems which comprise approximately 90 percent of the

TABLE 2
Number and Capacity of Utility FGD Systems

Status	Units	MW
Operational	51	17,822
Under Construction	42	15,763
Planned		
Contract Awarded	20	10,517
Letter of Intent	2	1,100
Requesting/Evaluating Bids	13	9,110
Considering FGD Only	34	17,174
Total	162	71,486

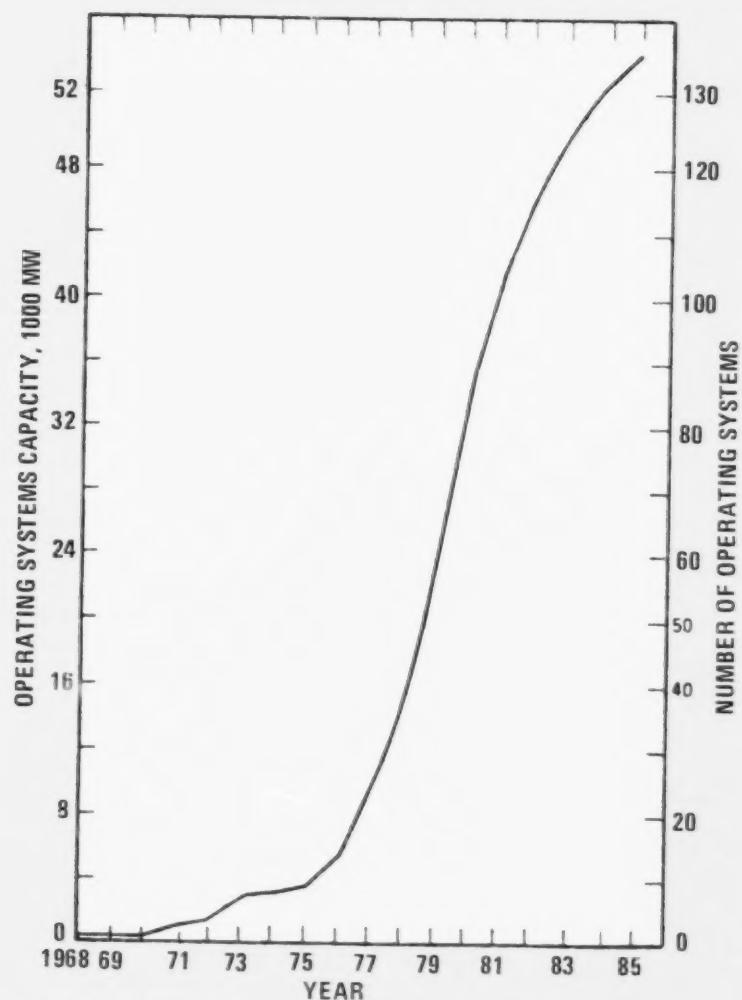


FIGURE 1—Projected FGD operating capacity, 1968 through 1986

units in operation, under construction or planned. However, considerable interest has surfaced within the utility industry with regard to dry scrubbing systems for low sulfur coal applications which offer the potential for simplicity (hence improved reliability) and lower costs. Three full-scale utility dry scrubbing systems are currently on order with startup scheduled for mid-1981-1982.

The spectrum of FGD processes currently in operation in the U.S. for control of SO₂ emissions from full-scale utility systems is shown in Table 3. These are summarized by process type, number of systems, controlled generating capacity and percentage of the total for each type.

TABLE 3
Operating Utility FGD Systems

Process	No. of Units	Controlled Generating Capacity, MW	Capacity, % of Total
Dual Alkali	2	553	3
Limestone Slurry	21	7386	42
Lime Slurry Scrubbing	18	6677	37
Lime/Alkaline Fly Ash	1	405	2
Limestone/Alkaline Fly Ash	2	1480	8
Soda Ash Solution	3	375	2
Magnesium Oxide	1	120	1
Wellman-Lord/Allied Chemical	3	826	5
Total	51	17822	100

Tables 4 and 5 summarize the current status of industrial boiler FGD applications in the U.S. (4). Where the utility industry has leaned heavily toward lime/limestone systems, the vast majority of industrial boiler FGD applications employ nonregenerable sodium based systems.

TABLE 4
Number and Capacity of Industrial Boilers FGD Systems

Status	FGD Systems	Boilers	Sites	Capacity 10 ⁻³ SCFM
Operational	126	232	36	5,465
Under Construction	24	48	12	1,102
Planned				
Contract Awarded	5	7	4	196
Letter of Intent	0	0	0	0
Requesting/Evaluation Bids	2	2	1	140
Considering FGD Only	6	16	4	1,603
Total	163	305	57	8,506

TABLE 5
Summary of Operating Industrial Boiler
FGD Systems By Process Type

Process	Capacity, 10 ⁻³ SCFM
Sodium Hydroxide/Sodium Carbonate	3,819
Dual Alkali	722
Limestone	55
Lime	40
Caustic Waste Stream	665
Ammonia	164
Total	5,465

THROWAWAY AND SALABLE FGD PROCESSES

The various FGD processes may be divided into two categories: regenerable and nonregenerable (perhaps more properly into salable product and throwaway processes). The regenerable or salable product processes produce sulfur, sulfuric acid, liquid SO₂ and possible gypsum if there is a market for it. (However, if impure gypsum is produced and is disposed of as solid waste, the system would be classified as throwaway.) Throwaway or nonregenerable systems produce a liquid, solid, or sludge waste product containing the sulfur removed from the flue gases. Of the systems appearing in Tables 3 and 5, only magnesium oxide and Wellman-Lord/Allied Chemical are salable product processes.

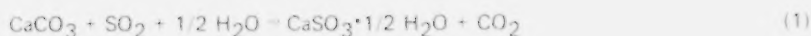
It is interesting to note that, although only 2 percent of the utility systems (the soda ash systems) produce a sizeable liquid waste stream, 83 percent of the nonutility applications (soluble alkali, throwaway) produce such a stream. In general, disposal of large volumes of liquid wastes containing soluble solids is environmentally unacceptable. Also, the cost of soluble alkali reagents is higher than calcium based alkali. In most cases a permit for such operations must be secured from the appropriate regulatory authority. Since utility systems are generally larger than nonutility systems, discharge permits for such operation may be less likely obtainable and reagent cost considerations thus become more significant. Most soluble throwaway systems either treat the soluble waste stream to reduce chemical oxygen demand (COD) and then feed the waste through some municipal wastewater process or simply evaporate the liquid.

Brief descriptions of most of the significant U.S. operating process types are given below.

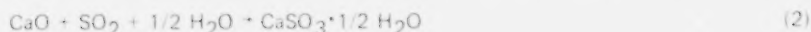
LIME/LIMESTONE SLURRY SCRUBBING

In concept, lime or limestone slurry scrubbing processes are very simple. In practice, however, the chemistry and system design for a full-scale operation can be more complex than seems evident at first glance. These systems use a slurry of lime or limestone in water to absorb SO₂ from power plant flue gas in a gas/liquid scrubber. The slurry generally ranges from 5 percent to 15 percent solids. Various types of scrubbers or gas/liquid contact devices are employed commercially: spray towers, grid towers, plate towers, venturis, marble-bed scrubbers (packed beds of glass spheres), and turbulent-contact absorbers (lightweight hollow plastic spheres—ping-pong balls—held between restraining grids in a countercurrent scrubbing tower). These scrubbers usually operate with a liquid-to-gas (L/G) ratio of 6 to 15 1/normal m³ (40 to 100 gal/1,000 actual ft) (3).

The overall absorption reaction taking place in the scrubber and the hold-tanks for a limestone slurry system produces hydrated calcium sulfate:



With a lime slurry system, the overall reaction is similar but yields no CO_2 :



(The actual reactant in Equation 2 is Ca(OH)_2 , since CaO is slaked in the slurring process.)

In practice, some of the absorbed SO_2 is oxidized by oxygen which is also absorbed from the flue gas. This shows up in the slurry as either gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or as a calcium sulfite/sulfate mixed crystal $[\text{Ca}(\text{SO}_3)_x(\text{SO}_4)_y \cdot z \text{H}_2\text{O}]$. Slurry is recycled around the scrubber to obtain the high liquid-to-gas ratios required. A bleed stream is taken from the scrubber liquid circuit to remove the calcium-sulfur compounds formed. This is accomplished by thickening, filtration, ponding, and various combinations of these operations. The calcium-sulfur compounds are solids to be disposed; the liquor separated is usually recycled to the system.

Lime and limestone slurry scrubbing systems can be engineered for almost any desired level of SO_2 removal. Present commercial utility systems are generally designed for 80 percent to 90 percent removal; however, higher removals have been achieved. The higher removal rate is not incrementally very costly: investment savings realized in designing for 80 percent rather than 90 percent SO_2 removal amount to only about 3.2 percent to 4.5 percent(5).

ALKALINE FLY ASH SCRUBBING

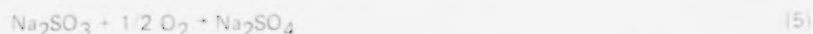
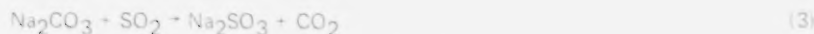
Western U.S. low-sulfur coals appear particularly suitable to SO_2 control by scrubbing the waste gases with a slurry of the alkaline fly ash which results from the combustion process (6). There are two ways to add the alkaline ash to the system:

- Collecting the fly ash in an electrostatic precipitator upstream of the scrubber and then slurrying the dry fly ash with water so that it can be pumped into the scrubber circuit
- Scrubbing the fly ash directly from the flue gas by the circulating slurry of fly ash and water

Most western coals have a low sulfur content (less than 1.0 percent). They also usually have a low heating value and consequently require close control to hold their combustion emissions within current Federal limits for NSPS defined as mass emissions per unit heat input. Whereas typical eastern bituminous coals have heating values of about 28,000 J/g (12,000 Btu/lb), lignite coals may have heating values as low as 16,000 J/g (6,800 Btu/lb). The bituminous coal could contain as much as 0.7 percent sulfur and still meet the old NSPS limitation of 520 ng/J without controls, but the lignite would have to have no more than about 0.4 percent sulfur due to its lower heating value. Generally, the coals best suited to this method are the western lignites and subbituminous coals. Certain of these coals (e.g., those from North Dakota, Montana, and Wyoming) contain up to 20 percent ash; and the ash contains up to 40 percent alkaline constituents including oxides of calcium, magnesium, sodium, and potassium, some of which are offset by acidic constituents. With the revised NSPS, this process may, however, have to be used with supplemental lime or limestone to meet standards.

SODA ASH SCRUBBING

The soda ash scrubbing method of controlling SO_2 involves scrubbing the flue gas with a solution of sodium carbonate and bicarbonate to produce a mixture of sodium sulfite and sulfate by these reactions:



The sodium carbonate does not have to be pure. Nevada Power Company uses trona salt, a naturally occurring mineral containing 60 percent NaHCO_3 , 20 percent NaCl , 10 percent sulfates, and 10 percent insolubles. This process has definite limitations in large-scale utility applications, since it requires a relatively cheap source of sodium carbonate or bicarbonate and an ability to dispose of large volumes of waste salt solution. Nevada Power is located near trona deposits—in an area where natural evaporation rates far exceed rainfall and where land is relatively abundant. The company processes its liquid waste in solar evaporation ponds and deposits the crystallized waste salts back at the mine.

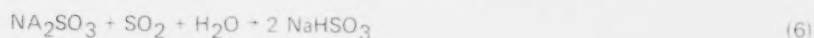
MAGNESIUM OXIDE SCRUBBING

The magnesium oxide process is a regenerable or salable product process. It does not produce waste material; SO_2 removed from the flue gas is concentrated and used to make marketable H_2SO_4 or elemental sulfur. Employing a slurry of MgO —or Mg(OH)_2 —to absorb SO_2 from flue gas in a scrubber, this process yields magnesium sulfite and sulfate. When dried and calcined, the mixed sulfite/sulfate produces a concentrated stream (10 percent to 15 percent) of SO_2 and regenerates MgO for recycle to the scrubber. Carbon added to the calcining step reduces any MgSO_4 to MgO and SO_2 . In commercial applications, the scrubbing and drying steps would normally take place at the power plant. The regeneration and H_2SO_4 production steps might be performed at a conventional sulfuric acid plant. Alternatively, a central processing plant could produce sulfur from mixed magnesium sulfite/sulfate brought in from several desulfurization locations.

WELLMAN-LORD SYSTEM

The Wellman-Lord process is also a regenerable or salable product system. When coupled with other processing steps, it can make salable liquid SO_2 , H_2SO_4 , or elemental sulfur.

The Wellman-Lord process employs a solution of Na_2SO_3 to absorb SO_2 from waste gases in a scrubber or absorber, converting the sulfite to bisulfite:



Thermal decomposition of the bisulfite in an evaporative crystallizer regenerates sodium sulfite for reuse as the absorbent:



The evaporative crystallizer produces a mixture of steam and SO_2 and a slurry containing sodium sulfite/sulfate plus some undecomposed NaHSO_3 in solution. As water condenses from the steam/ SO_2 mixture, it leaves a wet SO_2 -enriched gas stream to undergo further processing for recovery of salable sulfur values.

Most industrial boilers use a soluble alkali scrubbing process—basically as described for soda ash scrubbing, and using sodium carbonate, bicarbonate, hydroxide, or ammonia based alkali—which converts sulfur in the flue gas to sulfite/bisulfite and sulfate in solution. Disposal practices for spent scrubbing liquors include consumption in pulp/paper manufacturing, storage in evaporation ponds, and treatment (mainly by air oxidation) and discharge to sewer system/waterways. Some sodium-alkali users are considering regeneration of scrubber liquor by treating the spent liquor with calcium hydroxide. This would actually give them dual alkali systems with the attendant advantage of eliminating a liquid-waste stream.

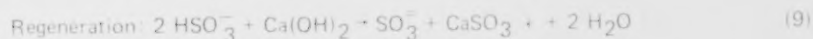
DUAL ALKALI

Table 5 shows that dual alkali systems have become the second most prevalent type of SO_2 control for industrial boilers. They may become the first choice as more sodium alkali systems are converted to dual alkali in the face of new regulations that may limit disposal of liquid wastes containing large amounts of dissolved salts. Dual alkali processes, like lime/limestone slurry scrubbing, are throwaway systems. In the operation as a whole, lime is consumed to produce a wet solid waste (mainly calcium sulfite/sulfate) just as in lime slurry scrubbing. In addition, however, dual alkali systems require a small amount of sodium alkali makeup.

A solution of sodium sulfite/bisulfite and sulfate in a scrubber will absorb SO_2 from the flue gas or other waste gas. Only the sulfite is active in absorbing SO_2 , forming bisulfite as in the Wellman-Lord system:



The bisulfite-rich liquor, treated with lime in a reaction tank, regenerates active alkali for recycle to the scrubber:



The sulfate and sulfite precipitate as a hydrated mixed crystal, or as a gypsum phase ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$) plus a hydrated mixed crystal, depending upon the concentration of dissolved species. Also, depending upon solution concentrations, the mixed crystal is predominantly calcium sulfite, with up to about 25 percent calcium sulfate coprecipitated. Sulfite/bisulfite oxidation by oxygen in the flue gas produces sulfate in the system.

RD&D PROGRAM RESULTS

The 1970 and 1977 Amendments to the Clean Air Act provide the authority for EPA's current research, development, and demonstration program in the FGD area. EPA's FGD RD&D program is conducted by the Industrial Environmental Research Laboratory at Research Triangle Park, N.C. (IERL-RTP). The primary purpose of this program has been to improve, develop, and demonstrate reliable, cost-effective and environmentally acceptable FGD processes for reducing SO_x emissions from both existing and new stationary combustion sources. EPA has been aided in this effort by at least two other Federal organizations, the Tennessee Valley Authority (TVA) and the U.S. Bureau of Mines (USBM). For example, EPA's key program in the nonregenerable area is the lime/limestone prototype test program at TVA's Shawnee Steam Plant (near Paducah, Kentucky), and a major regenerable process (citrate) demonstration unit is being built at a St. Joe Minerals plant based on pilot plant work by USBM. In addition, the Department of Energy is expected to play a major role in the FGD technology development area in the near future.

In the Federal Interagency Energy/Environment Research and Development Program, FGD technology development has been given a high priority. Studies by EPA indicate that FGD is competitive in cost with advanced control methods such as chemical coal cleaning and fluidized bed combustion; therefore, FGD should play an important role in controlling emissions at least until the end of the twentieth century. FGD technology has progressed rapidly in part due to financial aid passing through the Federal Interagency Program. A number of FGD supporting studies, pilot plants, prototypes, and demonstration-scale facilities have been funded by EPA supplementing progress in FGD development by the private sector. Some of the more significant current Federal FGD programs are summarized below.

PROTOTYPE FACILITY

The focal point of EPA's lime/limestone development effort has involved the operation of a prototype scrubbing test facility of TVA's Shawnee Steam Plant in Paducah, Kentucky. This versatile facility allows comprehensive testing of three 10 MW scrubber types under a variety of operating conditions and has been in operation since 1972. Bechtel Corporation of San Francisco designed the test facility and directs the test program. TVA constructed and operates the facility. Funding for the construction, operating, and maintenance of the facility has been provided by EPA.

The major concerns of the utility industry to date regarding lime/limestone scrubbing have centered on process reliability, the large quantities of waste sludge generated, and the high costs (capital and operating) of scrubbing. It is toward these areas of concern that the Shawnee program has been directed.

Major objectives of the original test program were:

- To characterize fully the effect of important process variables on SO_2 and particulate matter removal
- To develop and verify mathematical models to allow scaleup to full-scale scrubber facilities

OBJECTIVES OF SHAWNEE TEST PROGRAM

- To study the technical and economic feasibility of lime/limestone scrubbing, and
- To demonstrate long-term reliability.

The Shawnee program was subsequently extended and the scope expanded to investigate promising equipment and process variations to:

- Minimize costs, energy requirements, and quantity (and improve the quality) of the sludge produced
- Maximize SO₂ removal efficiency
- Develop a design/economic study computer program, and
- Improve system control and operating reliability, especially in the mist eliminator area.

Of particular interest have been studies of forced oxidation, increased alkali utilization, MgO and organic acid additives to increase SO₂ removal efficiency and to force sub-saturated gypsum operation.

The Shawnee program has made major contributions toward improvement of lime and limestone scrubbing technology. Recent results are of particular importance since over 90 percent of the approximately 75,000 MW of coal-fired electrical generating capacity in the U.S. presently committed to the use of FGD systems involve the use of lime/limestone processes. These results have shown substantial improvements in lime/limestone scrubbing systems in the areas of reliability, performance and waste disposal. Limestone utilizations exceeding 90 percent have been achieved with both single and double loop absorbers, thus reducing the limestone required and the calcium sulfite waste material produced for disposal. Forced oxidation of the calcium sulfite waste to calcium sulfate (gypsum) has been successfully demonstrated, enabling substantial reductions in the volume of waste produced and improvements in its disposal properties(7,8). Finally, the use of additives such as soluble alkalis or buffering acids (such as adipic acid) has been shown to dramatically enhance the mass transfer characteristics of limestone scrubbers and hence, enable attainment of SO₂ removal efficiencies exceeding 95 percent(9).

IN-HOUSE FGD PILOT PLANT

The EPA FGD pilot plant operated at IERL-RTP consists of two scrubbers having a flue gas capacity of about 0.1 MW. They have been in operation since 1972 to provide in-house experimental support for EPA's larger, prototype scrubber test facility at the Shawnee Steam Plant. The IERL-RTP scrubbers have 1 percent of the capacity of the Shawnee prototypes and are 1/1000 the size of a full-scale utility system. In addition to supporting Shawnee, the pilot plant also provides IERL-RTP with the capacity to independently evaluate new concepts in lime/limestone scrubbing technology. Many of the new concepts tested at Shawnee (such as forced oxidation and adipic acid additives) were first conceptualized and developed in the IERL-RTP pilot plant(10,11,12).

The feasibility of replacing freshwater makeup for limestone FGD systems with cooling tower or boiler blowdown has recently been established in the IERL-RTP pilot plant and operating limits defined(13). Further refinement of this development should make possible the integration of water treatment processes with FGD systems using forced oxidation. Such systems will maximize water reuse and minimize soluble salt discharges.

One of the pilot plant scrubbers was recently modified to allow testing of dual alkali systems with either lime or limestone regeneration. This will permit the in-house pilot plant to support EPA's development and demonstration efforts in dual alkali technology as it has supported the lime/limestone program in the past.

BAHCO SCRUBBER

EPA recently completed an 18-month test program at a lime/limestone industrial boiler FGD system installed to control SO₂ and particle emissions from seven small coal-fired heating boilers (approximately 23 MW equivalent, total) at the Richenbacker

Air Force Base near Columbus, Ohio. The FGD system was installed under contract between the Air Force and Research Cottrell, the U.S. licensee for the A. B. Bahco lime/limestone scrubbing process. This process was developed by A. B. Bahco, a Swedish company, and appears to be particularly well suited for industrial boiler applications in that it is manufactured in standard sizes in the range of 5-50 MW equivalent and is adaptable to a high degree of automation. The application of the Bahco scrubber at Rickenbacker was the first such installation in the U.S. and the first shutdown in September, a new baseline test was completed and the demonstration testing was reinitiated; the system has been in operation since that time. The integrated system is consistently achieving 91 percent SO_2 removal, particulate emissions of 0.04 lb/10⁶ Btu, and a sulfur product of 99.9 percent purity; sodium carbonate makeup anywhere on a coal-fired industrial boiler. The system met or exceeded all emission and operating cost guarantees. A final report on this program is currently available(14).

Additional EPA-sponsored work conducted at the site involved the evaluation of lime sludge (a waste product from water treatment plants) as an alternate SO_2 removal reagent. Results of the experimental program demonstrated that lime sludge is effective and offers significant cost savings over conventional lime/limestone reagents. Since lime sludge is widely available in many midwestern states where high sulfur coal is extensively used, it could find application for industrial boilers. A report describing these results will be published in November 1979.

FULL-SCALE DUAL ALKALI DEMONSTRATION

In September 1976, EPA contracted with Louisville Gas and Electric (LG&E) for a cost-shared, full-scale coal-fired utility demonstration of the dual alkali process at the 280 MW Cane Run No. 6 boiler. The demonstration project consists of four phases:

- Design and cost estimation
- Engineering design, construction, and mechanical testing
- Startup and performance testing
- 1 year of operation and long-term testing

Construction was completed in April 1979 and startup operations are currently under way. Phase 4 is expected to begin in November 1979. The FGD system was designed by Combustion Equipment Associates and Arthur D. Little, Inc. and was constructed by LG&E. In June 1977 a contract was established with Bechtel National, Inc. to design and conduct a test program to evaluate the system installed at LG&E. A report on the Phase 1 preliminary design and cost estimate for the system has been published(15). In addition to the design and cost estimate for the LG&E system, it also gives cost projections for similar hypothetical systems in the 500 and 1000 MW range. The report projects the LG&E system costs at less than \$60/kW capital cost and less than 3 mills/kWhr annualized operating costs in 1976 dollars.

WELLMAN-LORD/ALLIED CHEMICAL DEMONSTRATION

EPA and Northern Indiana Public Service Company (NIPSCO) have jointly funded the design and construction of an FGD demonstration plant using the Wellman-Lord SO_2 recovery process and the Allied Chemical SO_2 reduction process to convert recovered SO_2 to elemental sulfur. The operational costs for the system are being paid by NIPSCO, and a comprehensive test and evaluation program, conducted by TRW Corporation, has been funded by EPA. The demonstration system has been retrofitted to the 115 MW coal-fired unit 11 at the D.H. Mitchell Station in Gary, Indiana.

The demonstration program consists of the following phases: Phase I—the development of a process design, major equipment specification and a detailed cost estimate—was completed in December 1972. Phase II—the final design and construction—was completed by Davy Powergas, Inc. in August 1976.

Since the completion of startup activities, the plant has been operated by Allied Chemical under contract with NIPSCO. During the demonstration, a comprehensive test and evaluation program is being carried out by TRW, under contract with IERL-RTP. Integrated operation was achieved in August 1977, at which time the

Acceptance Test was successfully completed(16). The demonstration test year began in September 1977 but boiler and interface problems prevented acceptable operations until August 1978, after which 40 days of successful integrated operations were completed. Following system modification and maintenance during the scheduled boiler and utilities costs are within design targets. The FGD plant is following normal boiler operation (startup, shutdown, load changes, fuel changes, etc.) during the demonstration. The primary concern during the testing is the collection and evaluation of performance and economic data. TRW has prepared an interim report which presents the data collected over the first year of testing(17). A second, final, report will be prepared at the end of the second year of testing.

AQUEOUS CARBONATE DEMONSTRATION

EPA, EPRI, DOE and Empire State Electric Energy Research Corporation (ESEERCO), a research organization sponsored by New York's eight major power suppliers, have contracted to fund jointly the design and construction of a demonstration of Atomics International's sulfur-producing aqueous carbonate process(18). The demonstration is being retrofitted to a 100 MW boiler at Niagara Mohawk Power Company's coal-fired Huntley Station in Tonawanda, New York.

The demonstration is in four phases. Phase I, the design and cost estimate, was completed in May 1977. Phase II, construction, is expected to be completed by mid-1982. Phase III, acceptance testing, and Phase IV, an 18-month demonstration testing period, will follow.

CITRATE DEMONSTRATION PROGRAM

EPA and U. S. Bureau of Mines (USBM) have entered into a cooperative agreement to pool funds and technical talents to demonstrate the citrate process, a regenerable sulfur producing process, which has been developed through pilot scale by USBM. A concurrent development program, carried out by an industrial consortium headed by Pfizer Chemical Company, also led to a pilot operation of the process. Based on the results of these two pilot programs, EPA and USBM have initiated the demonstration of this technology on a 50 MW coal-fired boiler at St. Joe Minerals Corporation in Monaca, Pennsylvania(19).

The demonstration is in four phases. Phase I, the design and cost estimate, was completed in November 1976. Phase II, detailed design, procurement, and construction, began in March 1977 and was completed in July 1979. Acceptance testing, Phase III, should be accomplished in October 1979 at which time a 1-year test and evaluation program, Phase IV, will be initiated.

DRY SO₂ CONTROL PROGRAM

IERL-RTP accelerated its dry SO₂ control program early in 1979 through support of two surveys. One survey concerns the economics of dry scrubbing and is being performed by TVA. The initial objective of this study is to provide an expeditious economic comparison of the most promising application of a lime sorbent dry scrubbing system treating flue gas from western coal (0.7 percent sulfur, high alkalinity) with state-of-the-art wet limestone scrubbing. The report on this objective is slated for mid-August 1979 and will serve as an interim in-house reference. The final report, which is to be prepared by TVA in mid-1980, will include process information from vendors and cover the three methods of dry FGD technology—spray dryer-baghouse, dry sorbent duct injection (prior to baghouse), and dry sorbent boiler injection—limestone injection via low NO_x burner. The second survey serves to summarize the status of dry FGD processes in the United States for both utility and industrial applications. The Radian Corporation has completed a draft report which is now undergoing EPA's review. Publication of this state-of-the-art report is expected by mid-October 1979. Quarterly updates of this survey for this rapidly developing technology field are planned during FY 80.

Three EPA-sponsored demonstrations of dry FGD systems are in the planning stages with three different vendors. One demonstration would involve a full-scale industrial-size boiler (100,000 lb steam/hr), using Eastern coal (1-2 percent sulfur) and a spray dryer-baghouse system with lime as sorbent. This system at Celanese's Amcelle Plant (Cumberland, Maryland) is under construction and is expected to be operational in March 1980. These tests are expected to provide data relevant to establishing NSPS for industrial boilers.

Two pilot-scale projects at Western utilities are under consideration. Both would involve spray dryer-baghouse systems and scrubber waste characterization. However, a sodium compound (nahcolite) would be a sorbent at one site where evaluation of dry sorbent injection as an SO_2 removal method is also an objective. At the second site, comprehensive testing over 6 months of a system using lime as sorbent in a system handling 5,000 to 10,000 acfm of flue gas is planned.

If plans materialize, the full-load data for the full-scale industrial boiler scrubber tests should be available by June 1980, and the final report should be completed in September 1980. Reports for the two pilot demonstrations at utility sites are expected to be completed by the fall of 1981.

OTHER FGD SUPPORT PROJECTS

In addition to the current pilot and demonstration programs, previously discussed, other EPA-funded support activities in the FGD area include design and cost evaluations for advanced SO_2 removal technologies, byproduct marketing studies, bench-scale research on key processing steps, investigation of reductants for SO_2 to sulfur, energy optimization studies, and an assessment of flue gas reheat needs. To complement these control technology development efforts, companion technology transfer efforts are also under way. Through a series of briefings, symposia, capsule reports, summary reports, and a survey of FGD installations, the industry is being aided in its efforts to stay abreast of the rapidly advancing FGD technology. These technology transfer efforts include reporting the status of the many full-scale utility and industrial FGD systems designed, constructed and operated under private funding.

The use of high-sulfur coal will likely continue to increase in the coming years as a result of the Administration's National Energy Plan. The application of FGD technology to both utility and industrial combustion sources is playing (and will continue to play) a critical role in enabling these sources to comply with provisions of the Clean Air Act.

The Federal Interagency FGD program participants have effectively worked with industry to further the development, demonstration, and appreciation of FGD technology. Utility application of FGD systems now includes over 70,000 MW of capacity either in operation, under construction or planned. This represents an increase of 27 percent over the preceding year.





Michael D. Shapiro

Mr. Shapiro:

The Fossil Energy Cleanup Technology Program is a relatively new part of the overall fossil energy research program, initiated this fiscal year. It is, nevertheless, an integral part of DOE's coal strategy, providing a critical link between the national goal to use more coal and the simultaneous maintenance of a healthy environment.

A major DOE objective is to continue to expand U.S. coal use by continuing present uses and ensuring that coal is a viable option for all new industrial and utility uses. Meeting this objective is not only an obvious adjunct to reducing dependence on oil imports, but a legal mandate established by this administration and the Congress through national energy legislation, primarily the Power Plant and Industrial Fuel Use Act. In the short term (between now and 1990), the primary mode of continued and expanded coal use is in direct combustion applications. Direct firing of power plants, boilers, and furnaces will account for 90 percent of total coal use in this period.

The level of coal use is contingent on favorable economics, good technical performance, and compliance with environmental limitations. In fact, only with environmental compliance will expanded coal use be acceptable in the United States. This is reflected not only in the permitting mechanisms established in the major environmental laws, but also in the implementing legislation for DOE's coal conversion program, where exemptions allowing oil and gas use can be issued because of technical inadequacies or the high costs of pollution control systems.

Coal use is controlled under several major environmental laws. Of primary importance is the Clean Air Act. The environmental performance required for both utility and industrial coal-burning facilities depends on the age and location of the facility. Most existing facilities must meet the emission limitations in the Clean Air Act's State Implementation Plans (SIPs). New facilities that commence construction before proposal of EPA's revised New Source Performance Standards (NSPS) must meet the current NSPS. However, future coal use will be increasingly affected by the stricter standards in upcoming NSPS revisions. All of this leads to a significant demand for control of air emissions associated with coal use. Several other Federal laws, aimed at toxics in drinking water, general waterways, and waste disposal, regulate solid waste and water discharge from coal facilities. To date, these laws have not had a major impact on coal-use economics, but EPA progress over the next several years will result in clearer and stricter requirements in these areas.

With these short-term and long-term pollution control needs in mind, an integrated Fossil Energy Cleanup Technology Program has been established. The goals of this program are to identify, research, develop, refine, and demonstrate a range of engineering approaches capable of the following:

- Removing flue gas pollutants for compliance with environmental standards.
- Removing undesirable components from process streams produced during gasification and/or combustion, thus protecting utilization equipment, such as turbines, fuel cells, and heat exchangers.

The DOE's overall fossil fuels program, focused on the removal of contaminants and pollutants, can be carried out before fuel use, during processing, and after combustion. The cleanup technology program covers only the last two areas, which use similar hardware and processes. These areas of activity are shown shaded in Figure 2. Other parts of the overall energy system are treated elsewhere, all fitting together in a systematic effort to advance and refine all practical methods of clean and inexpensive fossil fuel use. Selection of the optimal path is a case-by-case decision related to specific sites, fuel prices, energy needs, and regulations.

The technology program is organized into three areas:

- Flue gas cleanup
- Gas stream cleanup
- Technology support

FOSSIL ENERGY CLEANUP PROGRAM

TECHNOLOGY PROGRAM AREAS

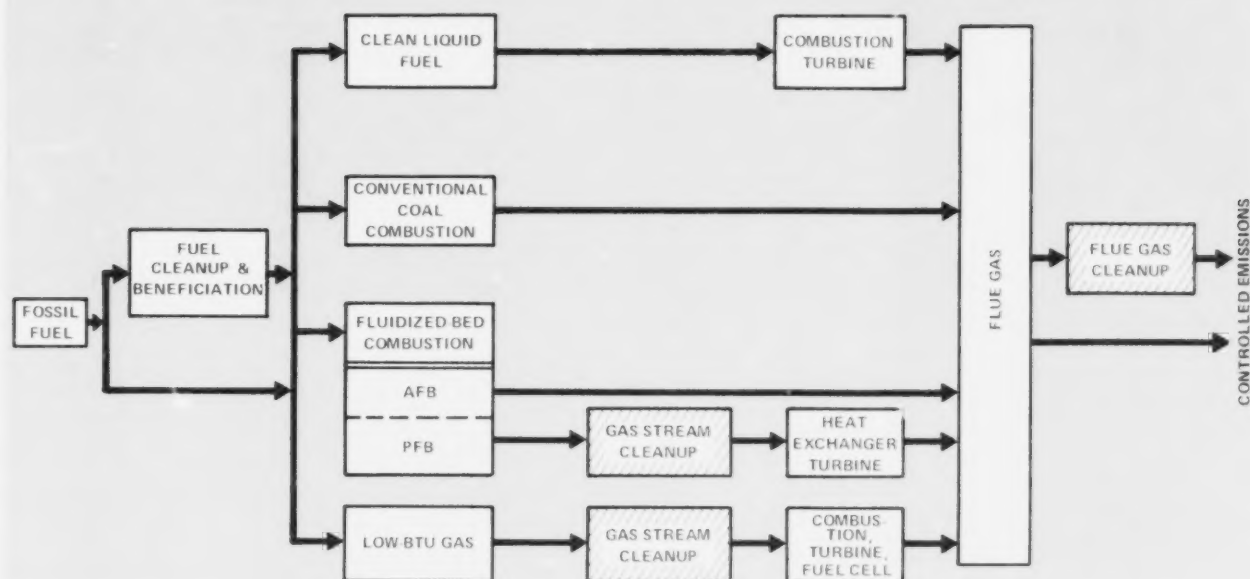


FIGURE 2—Cleanup technology control optics

Flue gas cleanup addresses the removal of air pollutants from the stack gases of conventional combustion units to meet environmental standards. Efforts focus on improving and demonstrating the reliability of conventional lime/limestone scrubbers, developing second-generation flue gas desulfurization (FGD) technologies that avoid wet sludge disposal, and initiating advanced technologies for removal of NO_x , particulates, and heavy metals. Gas stream cleanup includes the technology for removal of contaminants during combustion process or from the process stream prior to utilization. The key concerns are downstream hardware and environmental protection. Primary emphasis is on developing technologies to clean gas streams produced by coal gasifiers or fluidized bed combustors used in gas turbines, fuel cells, and heat exchangers. The objective is to remove sulfur compounds, particulates, and alkali metals. Technology support develops the crosscutting technologies in waste management, instrumentation and process controls, innovative concepts, and systems and economic comparisons, supporting both the flue gas and gas stream cleanup efforts.

PROGRAM COSTS

The funds appropriated for FY 1979 and the President's request for FY 1980 are shown in Figure 3. Of the \$7 million, \$2.7 million has been budgeted for the flue gas cleanup program for FY 1979. In addition, about half of the technology support budget is directly associated with flue gas cleanup problems, so the total budget related to flue gas cleanup is about \$4 million. In FY 1980, \$25.05 million, plus half of the technology support funds, for a total of \$28.55 million, has been requested for flue gas cleanup.

The first project in flue gas cleanup is to demonstrate the full-scale reliability of lime/limestone systems at acceptable cost. Our efforts to increase the reliability and reduce the costs of existing lime/limestone systems have many facets. In the area of erosion and corrosion, a cause of many failures, we will gather information on the properties of materials that affect the rate of erosion and corrosion. Any gaps will be filled using advanced instrumentation on existing test facilities, including the three 10-Mw units at TVA's Shawnee plant and the one at the Grand Forks Energy Technology Center.

	Funding (\$ Millions)		
	FY 78	FY 79	FY 80
Flue Gas Cleanup		2.7	25.05
Gas Stream Cleanup	NO	2.4	10.4
Technology Support	PRIOR	1.9	7.0
Capital Equipment	FUNDING	0	0.8
Total	0	7.0	43.25

FIGURE 3—Fossil energy cleanup technology budget summary

Process chemistry influences scaling, plugging, and overall removal efficiency. To understand these phenomena better, all existing data will be compiled and data gaps filled through parametric analyses at existing test units. The effectiveness of additives to control process chemistry will be tested for a range of coals, and the cost effectiveness of their use will be determined. In related research, forced oxidation of sludge and closed-loop operations will be field tested for their effectiveness in reducing the potential wastewater and solid waste impacts. Automated control systems, in concert with accurate process monitoring systems, promise real potential to both reduce costs and improve performance of the scrubbing system. Both the development and the testing of such systems will be supported.

To communicate the results of DOE's efforts to the persons designing, constructing, and operating lime/limestone scrubbers, DOE, in conjunction with the Electric Power Research Institute (EPRI), will produce a design manual for new systems and a maintenance guide for existing units. The design manual will help prospective FGD users select the best system as a function of size, coal type, applicable standards, and resource costs for the site in question. The maintenance guide will specify regular testing and/or maintenance activities to reduce the frequency of unplanned shutdown due to component failure, plugging, or scaling. In all of these work areas, when a significant improvement has been identified, DOE will support cost-shared evaluation of the innovation at a full-scale utility module.

ADVANCED FGD PROJECT

Lime/limestone systems essentially trade air pollution for solid waste pollution problems. In the advanced FGD project we hope to develop smaller, cheaper, less energy-consuming systems that minimize solid waste problems. A large number of processes have been proposed, many of which are sufficiently developed to permit a narrowing of choices for application from early 1982 through 1985. The processes are grouped as follows:

- Dry process - nonregenerable
- Double alkali process - nonregenerable
- All regenerable processes

PROPOSED PROCESSES

The dry processes, including sorbent injection, use limestone, nahcolite, trona, or the high alkali fly ash found in many western coals. The primary advantages of these systems are simplicity and reliability. Although they are not regenerable, the waste produced is a dry, more stable solid that does not require slurry ponds. The double alkali process, in which the SO₂ removal is done separately from the production of calcium sulfate sludge, can eliminate plugging and fouling problems and produce a more stable waste. Regenerable systems, wet and dry, produce a potentially saleable byproduct, such as elemental sulfur or sulfuric acid, but require a reducing agent, such as natural or coal-derived gas. The regenerable aqueous carbonate, Wellman-Lord, and magnesium oxide processes, for example, promise negligible secondary waste generation and are, therefore, very attractive long-term options.

ADVANCED CLEANUP PROGRAM TARGETS

As our efforts on lime/limestone reliability are completed, process parameters of advanced FGD systems will be investigated using the 10-Mw scrubbers at Shawnee and Grand Forks. The target of the advanced flue gas cleanup effort is greater control of the total spectrum of pollutants, with technologies available at acceptable costs by 1990.

For particulates, the focus is on improving conventional systems—electrostatic precipitators and fabric filters—to increase their efficiency in fine-particle control and to modify them for use under more rigorous conditions. Nitrogen oxide research emphasizes the evaluation of ammonia reduction and integrated systems that remove both sulfur and nitrogen oxides. The final element of the advanced cleanup program is examining the potential for exhaust emissions control for stationary engines, such as turbines and diesels, operating on high sulfur oil, coal liquids, or coal. We will examine the environmental impacts of such sources, if uncontrolled, and identify additional work needed.

INTERAGENCY ACTIONS

There have been several recent interactions between DOE's Office of Fossil Energy and EPA's Office of Energy, Minerals and Industry. We have signed an inter-agency agreement for the transfer of funds between the agencies. It allows for direct funding through EPA and also for joint funding of projects. In addition, we have prepared a cooperative planning document. The document includes a background describing the need for cooperation, the objectives of cooperation, the scope of the arrangement, the strategy for joint efforts, and management control plans.

The joint goals and objectives are to support the increased use of coal, as specified in the National Energy Act; to ensure that coal is managed in a manner that will protect public health and the environment; to improve the reliability and performance of available environmental control technologies for use by the electric utilities and industry; to minimize the capital and annual costs associated with environmental control; and to develop and demonstrate methods of disposing of or using solid waste created by coal use. Project areas included under the cooperative arrangement are SO_x control, both flue gas clean up and coal preparation; NO_x control, including flue gas treatment and combustion modification; particulate and contaminant control; waste management; and system optimization, which includes the combined control processes and supporting technologies.

JOINT EFFORTS

Strategy for the joint efforts includes separate funding and transfer of funds between the two agencies, technology transfer, joint cooperation on steering committees, and cost sharing of projects. In addition, to accomplish our goals, we must work very closely with EPRI, TVA, the utilities, and private industry.



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NITROGEN OXIDES CONTROL

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Nitrogen oxides (NO_x), principally nitric oxide (NO) and nitrogen dioxide (NO_2), are atmospheric pollutants having the potential for direct and indirect adverse effects on human health and welfare. Human activity originates emissions, resulting in NO_x concentrations in urban atmospheres that are 10 to 100 times higher than those from natural sources in nonurban areas. Fuel combustion in equipment contributes about 99 percent of technology-associated NO_x emissions. For most equipment about 95 percent of the NO_x is emitted as NO and 5 percent as NO_2 . In the atmosphere, NO_x enters into complex photochemical reactions with hydrocarbons and sulfur oxides and results in the formation of undesirable secondary species, with a shift of residual NO to NO_2 .

CLEAN AIR ACT OF 1970

The adverse effects of NO_2 and other pollutants on humans, animals, vegetation, and exposed materials were among the factors which led to passage of the Clean Air Act of 1970. With respect to NO_x , this Act empowered the EPA (a) to establish primary and secondary National Ambient Air Quality Standards (NAAQS) for NO_2 , (b) to require a 90 percent reduction in NO_x emissions from light duty motor vehicles, (c) to establish New Source Performance Standards (NSPS) for stationary sources, (d) to set up mechanisms to ensure compliance and enforcement, and (e) to provide research, development, and demonstrations of new and improved, commercially viable methods for the prevention and control of pollution from the combustion of fuels.

CLEAN AIR ACT AMENDMENTS

The Clean Air Act Amendments of 1977 require EPA (a) to revise the NAAQS for NO_2 to consider short term effects (not more than 3 hours), (b) to implement a revised level of automotive NO_x control, (c) to require NSPS based on use of the best technological continuous controls, and (d) to promulgate regulations for prevention of significant deterioration of air quality. The Amendments also require that any conversion of sources to coal firing be environmentally acceptable.

TABLE 1
Major sources of NO_x

Source	Percent of Stationary Source NO _x
Utility Boilers — Coal	31.2
Utility Boilers — Oil and Gas	14.7
Packaged Boilers — Oil and Gas	15.0
Packaged Boilers — Coal	5.9
Warm Air Furnaces — Oil and Gas	2.7
Engines	21.1
Miscellaneous Sources	9.4

TABLE 2
New source performance standards for steam generators

Fuel	NSPS (NO _x as NO ₂)	
	ng NO _x /J	lb NO _x /10 ⁶ Btu
Coal		
Bituminous	257	0.6
Subbituminous	214	0.5
Lignite		
Pulverized Fired	257	0.6
Cyclone Fired	343	0.8
Coal Derived Liquids	214	0.5
Oil	129	0.3
Gas	86	0.2

There are two areas under consideration for new or revised NSPS for steam generators. First, the available data are being reviewed to identify demonstrated technology for industrial boilers (less than 73 MW thermal, but greater than a not-yet-established lower limit). NSPS for both gas turbine and reciprocating engines are also being prepared. The gas turbine standard has been proposed at 75 ppm (at 15 percent O₂) for nitrogen-free fuels, with a stepped approach for fuel nitrogen up to a maximum of 125 ppm (at 15 percent O₂) for fuels with over 0.25 percent nitrogen.

POLLUTANT FORMATION

The primary emphasis in EPA's NO_x technology development program is on combustion modification to prevent pollutant formation. To optimize the control technology for any given fuel, it is necessary to understand the mechanisms by which NO_x is formed and destroyed during combustion. Two distinct sources of NO_x, identified by the terms thermal NO_x and fuel NO_x, are discussed below. In addition, it

This section of the paper provides information on combustion-generated NO_x which is necessary for a complete understanding of the EPA NO_x control program.

In the United States in 1976, NO_x emissions from human activity were estimated to be about 24.7 million metric tons per year. Of this amount, 45.0 percent was estimated to come from mobile sources, 51.7 percent from stationary combustion sources, and the remainder from miscellaneous sources. The stationary source NO_x can be subdivided by the type of source and fuel burned to give a better picture of the complexity of the problem. Table 1 represents the major divisions, but each source can be further subdivided by equipment design.

REGULATIONS

Existing regulations for NO_x fall into three categories: (a) ambient air quality standards, (b) stationary new source performance standards, and (c) mobile source standards.

To provide a basis for ambient air quality standards, available information was compiled and analyzed by an advisory committee. The areas covered included not only atmospheric chemistry, but also effects on materials, plants, and humans. A major conclusion was that the ambient concentration of NO_2 should be used as the basis of the standards. This was based on two main points. First, NO is rapidly converted to NO_2 in the atmosphere and, second, toxicology studies of NO and NO_2 show that NO_2 is the more hazardous form at concentrations found in the atmosphere.

As required by the Clean Air Act of 1970, National Ambient Air Quality Standards (NAAQS) for NO_2 were set in 1971. The primary standard is based on a level required to protect public health and the secondary standard protects the public welfare from any known or anticipated adverse effect associated with the presence of air pollutants in the ambient air. Both standards were set at $100 \mu\text{g}/\text{m}^3$ for NO_2 .

STANDARDS FOR NEW SOURCES

The Clean Air Act of 1970 required the EPA Administrator to set standards for new sources. The only source category for which Federal New Source Performance Standards (NSPS) are in effect is steam generators with a thermal input greater than 73 MW (250×10^6 Btu/hr). The initial NSPS for this class of equipment burning gas, oil, and coal (except lignite) became effective in 1971. The coal standards were revised in 1979 and a coal-derived liquids standard was added. The lignite standard, which was promulgated in 1978, is based on firing method; however, cyclone-fired boilers are only allowed for fuel containing greater than 25 percent lignite from North Dakota, South Dakota, or Montana. The NSPS are summarized in Table 2.

The basis of these regulations is combustion modification to reduce NO_x formation, and compliance is achieved with flue gas recirculation, staged combustion and/or altered burner designs.

Although the NO_x control strategy in the Clean Air Act of 1970 was predicated primarily on high level control standards for the automobile, the 1977 Amendments have eased the restrictions. The original standard of 0.24 mg/m (0.4g/mile) for 1978 has been retained only as a research goal. This relaxation of the automotive standard places increased emphasis on control of stationary source NO_x emissions. From the current standard of 1.9 mg/m (3.2 g/mile), the standard is reduced to 1.2 mg/m (2.0 g/mile) through the 1980 model year, and to 0.6 mg/m (1.0g/mile) for 1981 and later.

There are pending regulations based on the Clean Air Act Amendments and on establishment or revision of NSPS for stationary sources. Each major area is discussed briefly.

PENDING REGULATIONS

The Clean Air Act Amendments require that the EPA Administrator promulgate a short term NO_x ambient air quality standard unless he finds that there is no significant evidence that such a standard is needed to protect public health. The Act also provides that the period of such a standard should be from 1 to 3 hours. A review of acute short term NO_2 effects and the prevalence of critical levels of NO_2 in the atmosphere is underway and will be used as the basis of a decision for the revision of the existing standard.

is necessary to ensure that control technology does not adversely affect other pollutants or system efficiency. A brief discussion of these factors is also given below.

THERMAL NO_x

The fixation of a small fraction of the molecular nitrogen in the combustion air results in the formation of thermal NO_x . Since the activation energies of several of the formation reactions are high, the rate of formation of thermal NO_x is strongly temperature dependent. Thermal NO_x is formed during the combustion of all fuels in the regions of peak temperature that occur in all diffusion flames.

FUEL NO_x

The oxidation of nitrogen compounds chemically bound in the fuel molecule produces fuel NO_x . Since significant amounts of nitrogen (0.1 to 2 percent by weight) are found in all heavy fuels (residual oil and coal), fuel NO_x is a major contributor to the total NO_x from these fuels. Based on small scale experiments, 50 to 90 percent of the total NO_x from residual oil and coal is fuel related, even though it is well established that only a fraction of the fuel nitrogen is converted to NO_x , with the balance forming molecular nitrogen. The main factor affecting the conversion to NO_x is oxygen availability. The reactions appear to be relatively insensitive to temperature.

In general, a well designed boiler that is properly maintained and operated produces low levels of carbonaceous pollutants (CO, HC, carbon particulate). Other pollutant emissions (SO_x and inorganic particulate) from these sources are less a function of operation than of fuel composition and, in some cases, firing mode. On the other hand, stationary engines can emit significant amounts of CO and hydrocarbon. Since the combustion control techniques for NO_x require changes in the way fuel is burned, they also present the opportunity for optimizing the total combustion process to achieve low levels of other pollutants.

Several control techniques can be applied to stationary combustion. Combustion modification technology is the most cost effective and energy efficient for conventional combustion sources. For any technique the degree of control depends not only on the unit design but also on the fuel. Although NO_x reductions in excess of 80 percent relative to uncontrolled levels have been achieved by combustion modification, even greater control may be required. This may be obtained either by advanced combustion or by supplemental techniques such as ammonia injection and flue gas treatment. The various techniques are described briefly below.

DILUENT ADDITION

The most effective control of thermal NO_x is a reduction of the peak temperatures in the flame zone. One approach is the addition of an inert diluent to the fuel or air stream, thereby lowering the theoretical flame temperature at which combustion takes place. The two most common approaches are flue gas recirculation (i.e., the addition of relatively cool combustion gases recycled from the flue and mixed with the combustion air) and water injection (i.e., addition of water or steam to either the air or fuel stream). Of the two, water injection is the more effective on a mass basis due to the latent heat of vaporization effect; however, it imposes a stack heat loss that can be avoided with flue gas recirculation. These techniques are most effective for thermal NO_x and appear to have little effect on fuel NO_x . For example, 70 to 90 percent maximum reductions have been observed for natural gas and distillate oil in field and laboratory studies; for heavy oil, the range is 20 to 50 percent; and for coal, 10 to 30 percent. Flue gas recirculation alone or in conjunction with other techniques is used to achieve emission standards for gas and oil fired utility boilers. Its potential drawbacks are increased mechanical complexity and capital costs. Water injection is the state-of-the-art NO_x control technique for gas turbine engines.

STAGED COMBUSTION

Staged combustion is based on operation with a rich primary combustion zone in the furnace to reduce oxygen availability and peak temperature, followed by secondary air injection to achieve carbon burnout. The reduced oxygen availability reduces the conversion of fuel nitrogen to NO and the reduced peak temperature and subsequent heat removal prior to secondary air addition reduces thermal NO_x . One method of implementing this control is illustrated in Figure 1. The air supplied to the burners is less than the amount necessary to completely combust the fuel, which produces a fuel-rich primary zone. Although the effectiveness of staged combustion increases significantly as the primary stoichiometry is decreased toward 75 percent of theoretical air, actual coal furnace primary zone stoichiometry is limited to 95 to 100 percent

theoretical air by operational considerations (e.g., slagging, corrosion). The secondary air is added above the top row of burners and an equal or greater secondary zone residence time is provided for carbon burnout. Although up to 90 percent reduction of NO_x has been observed in coal fired laboratory systems, the maximum practical reduction achieved on field operating boilers under actual or experimental conditions is 30 to 50 percent. Staged combustion is used in a number of configurations to achieve the NSPS for coal fired steam generators and is also employed to meet standards for oil and gas fired units.

BURNER DESIGN

Although diffusion flame burners of many designs have been used in fuel combustion for years, only recently has the modification of design approaches to achieve emission control received strong emphasis. The essential elements of a diffusion

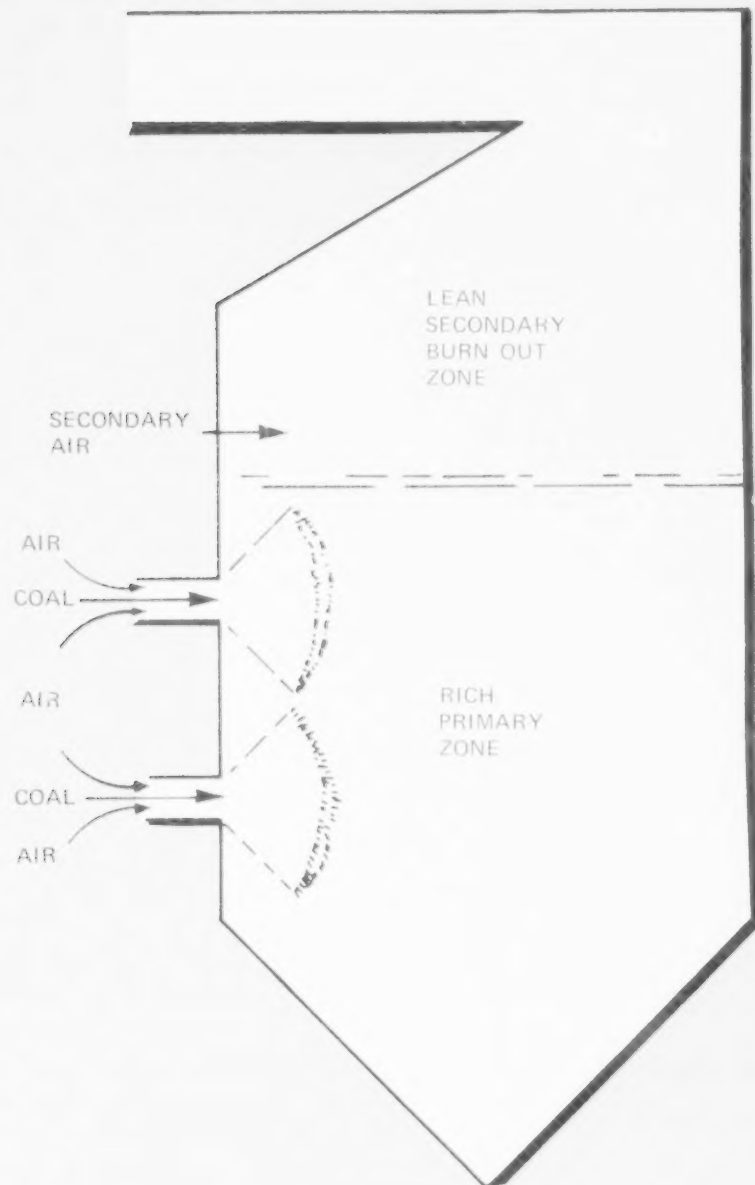


FIGURE 1—Staged combustion

flame burner are a fuel introduction system and a burner throat to supply combustion air. Design variables used to achieve stable combustion and good fuel conversion efficiency include fuel distribution (controlled by injector design) and the rate of air mixing (controlled by throat velocity, use of swirl, and/or design of the flame holder). These same variables can control fuel and air mixing histories for emission control; however, the flame characteristics required may be significantly different than the conventional practice. The fuel and air mix initially in a primary reaction zone which contains a wide range of stoichiometries, from very rich to very lean. This characteristic of diffusion flames appears to result in the partial conversion of fuel nitrogen to NO_x . The balance of the combustion air is mixed with the primary zone products farther downstream and combustion is completed. In addition, relatively cool combustion products recirculate within the combustion chamber and are entrained by the flame. This entrainment can provide a diluent effect which reduces peak temperature and, therefore, reduces thermal NO_x . Several pulverized coal burners designed to reduce NO_x have been tested by boiler manufacturers; reductions of 30 to 50 percent relative to uncontrolled levels have been achieved. A modified burner design is currently used by one manufacturer to achieve the NSPS for coal fired utility boilers. Entrained combustion gas recirculation burners have achieved NO_x reductions in excess of 50 percent for clean fuels (natural gas and distillate oil). In addition, several studies of advanced burner designs for heavy oil and coal have shown the potential for 65 to 90 percent reduction relative to uncontrolled emissions.

ADVANCED CONCEPTS

Alternate combustion approaches do not employ classical diffusion flames and, therefore, may allow very low levels of NO_x . For example, catalytic combustion, which is still being studied on the laboratory scale, has shown the potential for NO_x emissions below 10 ppm for clean fuels. Further development is required to assess the full potential of this emerging technology in practical systems.

The ammonia injection technique involves the injection of ammonia (NH_3) into the boiler firebox above the combustion zone and the subsequent reduction of the NO_x to N_2 by homogeneous reaction. The process requires careful NH_3 to NO ratio control and injection at the proper temperature. Reductions of 90 percent have been achieved in the laboratory and 40 to 60 percent in field operating boilers. Due to reagent requirements, it is anticipated that this technique will be used to supplement combustion control techniques where very low NO_x levels are required.

NO_x FLUE GAS TREATMENT

Many processes for NO_x flue gas treatment have shown the potential for high removal efficiency. Selective catalytic reduction processes using ammonia as the reductant are the most developed and most promising flue gas treatment processes. Although there are many variations, anhydrous ammonia is usually injected into the flue gas after the boiler economizer, and the resultant mixture is passed over a catalyst. The ammonia selectively reduces the NO_x in the presence of the catalyst to molecular N_2 which then passes out of the NO_x removal system and into the boiler air heater. Selective catalytic reduction processes can remove 90 percent of the NO_x from the flue gas of a combustion source. In Japan, selective catalytic reduction processes have been successfully installed on commercial-scale gas-and oil-fired sources and are planned for coal-fired sources. A variation of the process can simultaneously remove 90 percent of the NO_x and SO_2 in combustion flue gas. The process uses copper oxide to absorb the SO_x , and the resulting copper sulfate acts as a catalyst in the reduction of NO_x to N_2 with ammonia. A multiple reactor system is required to allow for continuous treatment of the flue gas and regeneration of the reactor saturated with copper sulfate. In the regeneration cycle, hydrogen is used to reduce the copper sulfate, and a concentrated SO_2 stream is produced which can be used to generate a salable by-product.

FUTURE TRENDS

The uncertainties of key variables make the quantitative prediction of future trends very difficult; however, several factors appear to indicate the need for more stringent NO_x control capabilities in several areas. Some of these are discussed briefly.

The National Energy Plan calls for a significant increase in coal utilization by industrial and utility sources. The actual increase depends on (a) coal production capability, (b) energy consumption growth rate, (c) nuclear energy expansion rate, (d) economics, and (e) environmental regulations. A first step is that virtually all new

utility boilers are coal fired. The result on NO_x emissions from this source can be generally illustrated by the fact that the current NSPS for coal-fired utility boilers are 2.3 and 3.5 times those for oil- and gas-fired boilers, respectively. With the 1971 NSPS for coal-fired utility boilers, one recent projection indicates that the increase in total NO_x emissions from 1972 to 2000 would be from 30 to 80 percent dependent on the assumptions of energy growth and nuclear capacity. Progressively higher levels of emission controls through 1988 are required to significantly reduce the rate of increase. Therefore, major emphasis on emission controls for coal-fired industrial and utility boilers appears to be imperative.

ALTERNATE FUELS

Significant effort is underway in the United States to develop and commercialize processes for producing alternative gaseous, liquid, or solid fuels from coal or shale. Although most of these processes significantly reduce two of the objectionable components (sulfur and mineral matter) associated with coal, they do not eliminate chemically bound nitrogen. Typically, liquid fuels derived from coal and shale have nitrogen contents from 0.5 to over 2.0 percent by weight. Although this nitrogen can be at least partially removed by hydrotreating, it is potentially an expensive and energy intensive process. Similarly, low and medium Btu fuel gas produced from coal has the potential for containing up to 4000 ppm NH_3 and cleanup, particularly at high temperature, remains difficult. Evidence indicates that combustion modification should be equally or more effective for alternative fuels than for coal and heavy petroleum oil. Further development of the technology on the specific fuels is required.

Very low levels of NO_x may be required under several circumstances. First, the short-term NO_2 standard being considered may require stringent control in certain areas. The degree of control and the specific sources requiring control for any given location have not been established. It is also not obvious if large point sources or area sources will be the prime target of control. Second, regulations requiring the prevention of significant deterioration may require very low levels of NO_x in certain areas if development is to take place. Finally, certain local situations may require increased NO_x control capability. All of these factors provide impetus for establishing the optimum control achievable by (a) conventional combustion, (b) advanced combustion, and (c) post combustion treatment.

NO_x CONTROL PROGRAM

The EPA's Industrial Environmental Research Laboratory at Research Triangle Park, N.C., is vigorously pursuing a program to develop and demonstrate NO_x control technology for a broad range of combustion sources burning a variety of fuels. Based on both experience and projections, major program emphasis is on coal combustion in industrial and utility boilers. Other source/fuel combinations are also covered, based on similar considerations. The program's technical approach is based on a balanced and coordinated mix of technology application, technology development, and fundamental research. In general, technology being readied for evaluation in field applications has been developed under EPA sponsorship. Optimization of the technology at the development stage has resulted from an empirical experimental approach and a complementary fundamental understanding of critical phenomena in the NO_x formation and destruction processes. The overall program has been discussed in detail previously in *Energy/Environment III* (EPA-600/9-78-022). The purpose of this paper is to summarize the significant technical progress over the past year. Specific program areas are discussed in detail below.

LOW NO_x COAL BURNER

Many, if not all, new utility and industrial boilers with a thermal input greater than 35 MW will be fired with pulverized coal. Wall-fired, field-erected watertube boilers constitute a dominant fraction of the capacity in these boiler classes. The low NO_x coal burner has the potential for direct application to new and existing boilers. The program consists of three major elements: (a) burner design and scale-up criteria, (b) extension of the applicability of the technology, and (c) field evaluation of its performance on practical boilers.

Since the control of both thermal and fuel NO_x from pulverized coal combustion is strongly dependent on the temperature and stoichiometry in the primary zone, the most direct approach is to redesign the burner to achieve the required fuel/air distribution. In 1971 the EPA initiated a small scale study to identify the important burner design parameters for NO_x control. This study identified a distributed air burner concept that had the potential for very low NO_x emissions with both high

carbon utilization efficiency and acceptable flame characteristics. This pilot scale work was carried out at thermal heat inputs of 1.5 to 3.0 MW, which is a factor of 10 to 40 less than practical pulverized coal burners currently in use. Due to difficulties in scaling burner thermal performance by even a factor of 2, current design practice is to make incremental capacity changes, or simply install more burners of the same size. Therefore, to obtain industry acceptance of the low NO_x burner technology, it was necessary to identify scaling criteria and to evaluate the burner performance at as close to practical size as possible. A project was initiated to develop scaling criteria for low emission burners. As an essential part of the program, a unique combustion facility capable of firing coal and other fuels at a thermal input up to 40 MW was designed, constructed, and used to study burner scale-up. The basis of the low NO_x coal burner is a distribution of the combustion air to control the reaction history of the coal. This is shown conceptually in Figure 2. The coal is introduced with primary air and the initial devolatilization reaction takes place at a very rich stoichiometric ratio (SR_1) which results in evolution of fuel nitrogen intermediates (XN) under conditions where oxidation to fuel NO_x is low. Secondary air is introduced in a way which provides a gradual leaning out of the reaction zone to a stoichiometry (SR_2) which is still fuel-rich. This gradual mixing allows formation of NO_x and a subsequent reduction by XN to form N_2 . Both the temperature and stoichiometry history of this rich reaction zone determine the level of NO_x that can be achieved. Finally, tertiary air is mixed with the reaction products to give a lean burnout zone (SR_3). In this zone any residual XN species are converted predominantly to NO_x , any nitrogen remaining in the char is converted predominantly to N_2 , and fuel species (char, CO , HC , H_2) are oxidized to give complete combustion. Complete reaction of the carbon in the char is especially important from the standpoint of both efficiency and emission performance.

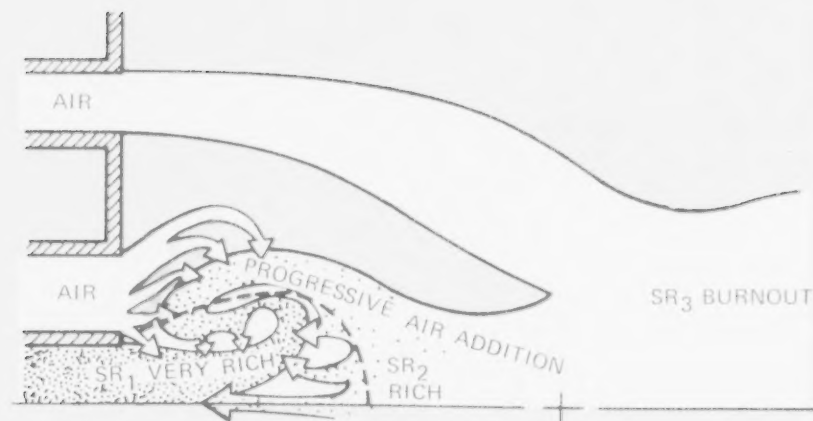


FIGURE 2--Conceptual sketch of low NO_x burner system

The design of one experimental burner used to achieve these conditions is shown in Figure 3. The design incorporates a retractable oil gun for use on startup and a divided secondary air channel to provide flexibility on turndown.

DESIGN FOR THREE FIRING RATES

In an attempt to optimize the burner performance, several other burner configurations have been evaluated. The initial evaluations of burner configurations are carried out at 4 thermal MW and promising designs are scaled up for testing at 16 and 35 thermal MW. The results for one design operating at optimum conditions for all three firing rates are shown in Figure 4 where NO_x emissions are plotted versus the combustion air supplied through the primary and secondary channels. In all cases the

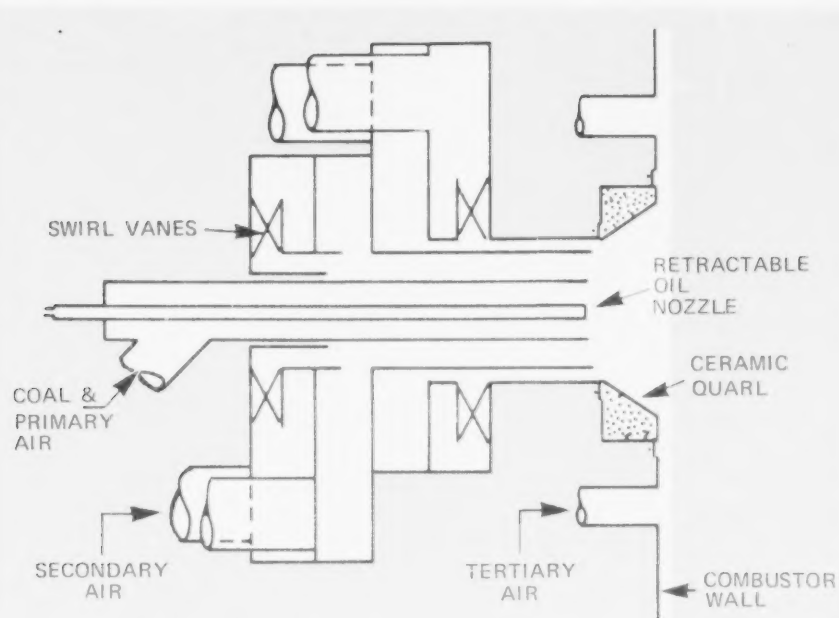


FIGURE 3—Sketch showing major features of 15-thermal-MW distributed mixing burner

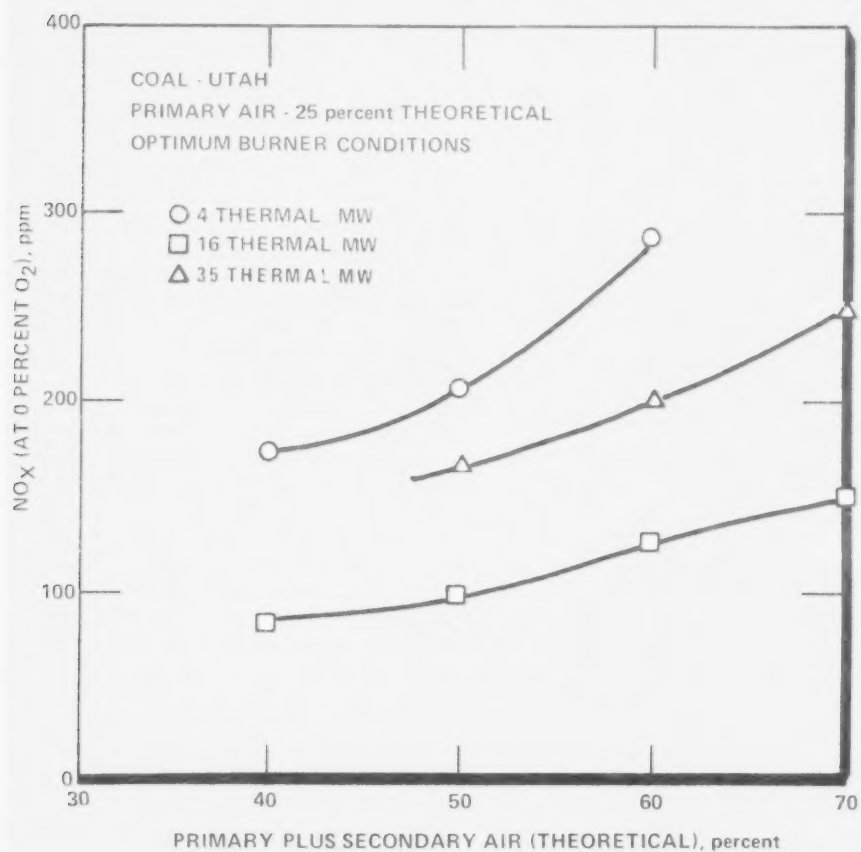


FIGURE 4—Effect of burner scale on No_x emissions

overall combustion air is 125 percent of the theoretical amount for complete combustion. The 4 thermal MW burner produces higher emissions than either of the two large burners. The 16 thermal MW burner produces emissions below 86 ng/J (approximately equivalent to 175 ppm at zero percent (O_2) for all primary zone conditions), while the 35 thermal MW burner achieves that level with 50 percent of theoretical air through the burner. The three burners are geometrically scaled to provide an evaluation of that approach to scale-up. Other burner design and/or scale-up approaches give similar overall trends, but have a significant effect on the operating conditions to achieve minimum emissions. The 16 and 35 thermal MW burners are in the size range of the burners used on practical boilers which provides additional confidence in the applicability of the technology.

FUEL SCREENING

Of all the fossil fuels currently used in the United States, coal is not only the most abundant, but also presents the most complex problem of combustion and emission control. In addition, there is no typical coal; properties of a given coal can vary within the same seam. In spite of the wide ranges of composition that affect both the way the fuel burns and the pollutant emissions, a general picture of the important pollutant formation mechanisms can be presented by discussing phenomena that occur in terms of a single coal particle. In fact, coal probably does not burn as single particles and the following discussion is phenomenological. For combustion in practical systems, pulverized coal is mixed with a fraction of the combustion air (called primary air) and introduced into the furnace through the fuel injector of the burner. The amount of primary air is determined by both the fuel properties and burner design; however, it is normally 10 to 30 percent of the theoretical air required for complete combustion. The actual stoichiometry under which any fuel particle reacts will depend on the fuel and air mixing history. The sequence of events occurring for a single coal particle is shown in Figure 5, which indicates two combustion modes (volatile evolution and char burnout) as discussed below. Although every coal particle undergoes similar types of processes, the environment under which pollutant formation reactions occur is governed by the aggregate coal particle cloud reaction history.

VOLATILE PORTION

As the coal particle is heated by radiation and convection, the volatile portion of the coal substance begins to evolve. The initial products contain carbon and hydrogen and probably represent side chains and cross linkages between the ring structures in the coal molecule. These initial volatiles react with the surrounding air and partially deplete the available oxygen. As the temperature increases and the ring structures begin to fragment, nitrogen-containing intermediates (designated XN) are evolved and begin to react with oxygen to form NO_x . Subsequent reactions of XN with NO_x and other species produce molecular N_2 . The amount of nitrogen evolved in the volatile fraction depends on the ultimate particle temperature; the fate of the XN compounds depends on the local stoichiometry around the particle. For fuel lean conditions, a substantial fraction will be converted to NO . For fuel rich environments, the production of molecular nitrogen increases until an optimum stoichiometry is reached; then, for even richer stoichiometries, the residual nitrogen species (XN) are retained unreacted and burn in leaner secondary combustion zones. It also appears that some of the NO_x formed can be reduced to N_2 by heterogeneous reaction with coal particles or char.

DEVOLATILIZATION

During this devolatilization process, inorganic and organic sulfur species are released as sulfur intermediates (designated XS). In general, the XS species are essentially quantitatively converted to sulfur oxides (SO_2 or SO_3) at some point during the combustion process; however, these species may undergo different reactions or may influence other reactions in this devolatilization zone. Two examples may be cited. First, a significant amount of the sulfur in some western coals can be retained in the ash, probably as a sulfate; however, this retention may be enhanced if the sulfur could be captured during devolatilization. Second, sulfur species can influence the conversion of nitrogen species (XN) to NO and other products; therefore, the history of sulfur intermediates relative to nitrogen intermediates (XN) is important in the devolatilization zone. Finally, a portion of the mineral matter from the coal is vaporized in the devolatilization zone and subsequently condenses and/or coalesces to form submicron particulate. The temperature and stoichiometry during devolatilization probably influences the potential for fine particulate formation.

CHAR COMBUSTION

Following devolatilization, the residual coal matter (called char) is burned out. The composition of the char depends strongly on the conditions in the devolatilization zone; however, its major components are generally carbon and mineral matter with variable amounts of nitrogen and sulfur species. By the nature of coal combustion, char combustion occurs under predominantly fuel lean conditions. By design, carbon burnout is nearly complete, thereby maximizing energy efficiency and minimizing the carbonaceous particulate. The residual nitrogen species in the char form NO and N_2 during burnout in a mode of combustion which appears to promote N_2 formation. The sulfur species are either oxidized to SO_2 or retained with the mineral matter. The residual mineral matter forms particulate (flyash) in the 0.1 to $50\text{ }\mu\text{m}$ size range. Simultaneous with char burnout, residual gaseous species (CO , H_2 , HC) must also be burned out. This mechanistic understanding of pollutant formation processes forms the basis for optimization of combustion techniques for emission control which are based on tailoring the air and fuel mixing history to minimize all objectionable species.

FUEL SCREENING EXPERIMENT

The effect of coal type on NO_x emissions has not been previously studied in a systematic manner under completely comparable conditions. In view of the potential for the nitrogen evolution and the fuel-air mixing histories for different coals, a fuel screening experiment was required to assess the applicability of the low NO_x burner technology to the range of U.S. coals. Initial screening is carried out at small scale, followed by more limited testing in large burners. The small scale experiments are

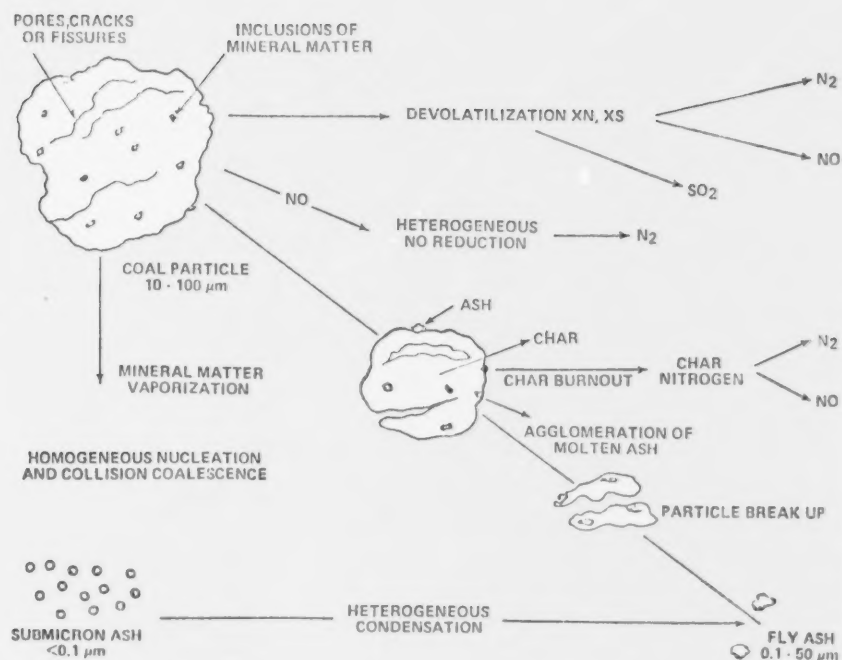


FIGURE 5—Pollutant formation during pulverized coal combustion

carried out in a downfired refractory furnace shown in Figure 6. The burner shown is an axial diffusion flame burner; however, other burner types are also used to assess the effect of primary air-fuel mixing on emissions. The oxidant can be either air or an artificial argon-oxygen mixture, which eliminates thermal NO_x . The system is being used to screen a large number of U.S. coals under both unstaged and staged conditions.

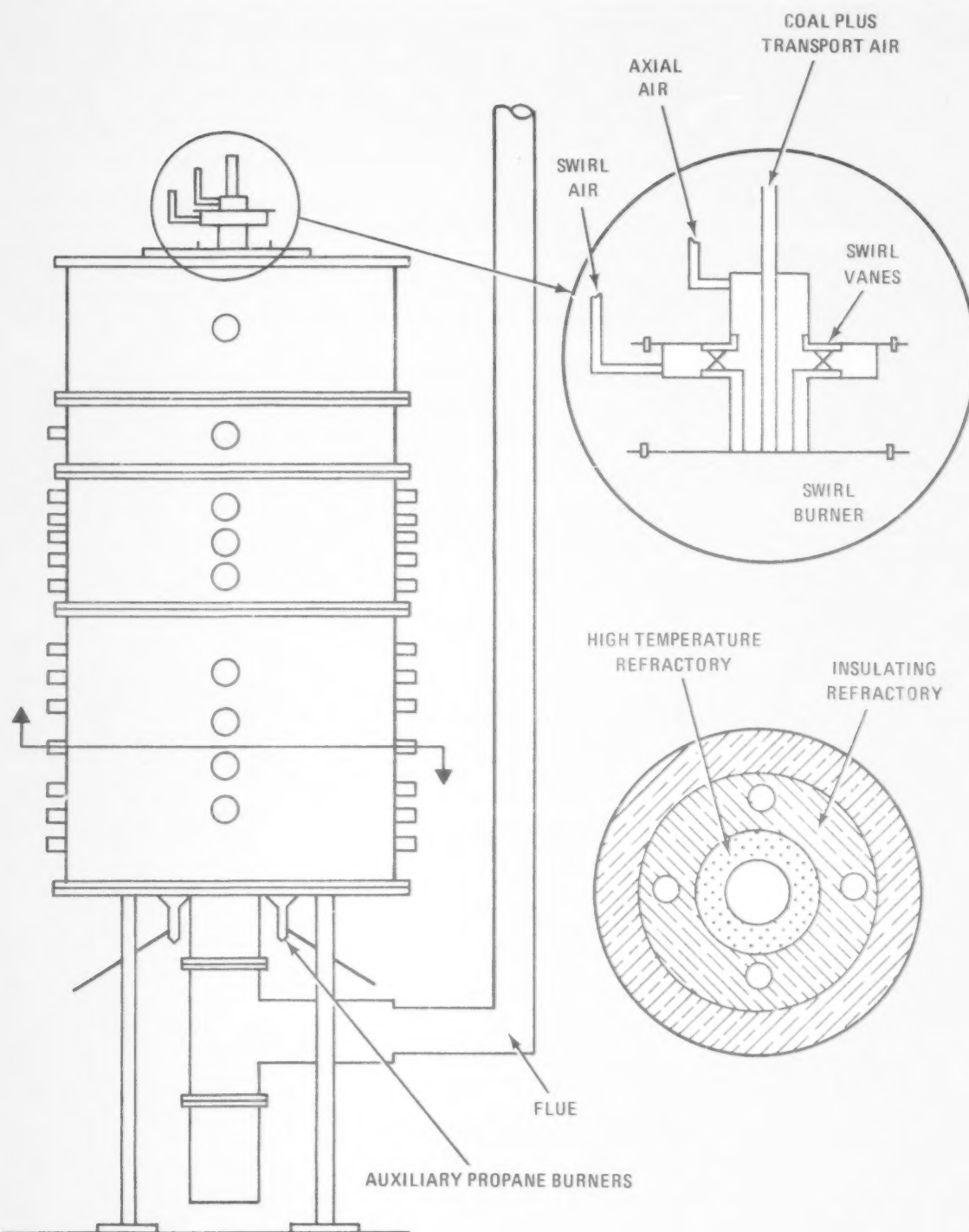


FIGURE 6—Small experimental facility

NITROGEN RANGE FOR U.S. COAL

The fuel NO_x levels versus fuel nitrogen content for representative coal types are shown in Figure 7 for the premixed fuel lean combustion mode. The data show the wide range of nitrogen content for U.S. coals from 0.83 percent for an anthracite to nearly 1.9 percent for medium volatile bituminous. The NO_x values shown are moderately to significantly higher than those measured for similar type coals in practical boilers. This is believed to be caused by the premixed system giving higher conversion of nitrogen compounds than occurs in diffusion flame burners. While the NO_x levels show a general trend to increase with increased fuel nitrogen, this is not the only variable as illustrated by comparing coals of similar type and/or nitrogen content. For instance, for the two lignites at about 1.2 percent nitrogen, the lower point is only 60 percent of the upper value. Similarly for the four high volatile bituminous coals at 1.4 to 1.6 percent nitrogen, the emissions range from 800 to over 1200 ppm with the lowest nitrogen content coal giving the highest number. Note that the highest number is produced by a Utah coal (1.4 percent nitrogen) which has been used for the bulk of the burner scale-up work. These data appear to indicate that the manner in which the nitrogen is bound in the coal affects the fractional conversion to NO_x at a constant operating condition. Although it has been postulated that the fraction of the nitrogen evolved with the volatile matter is the important variable, a technique for characterizing the differences has not yet been found.

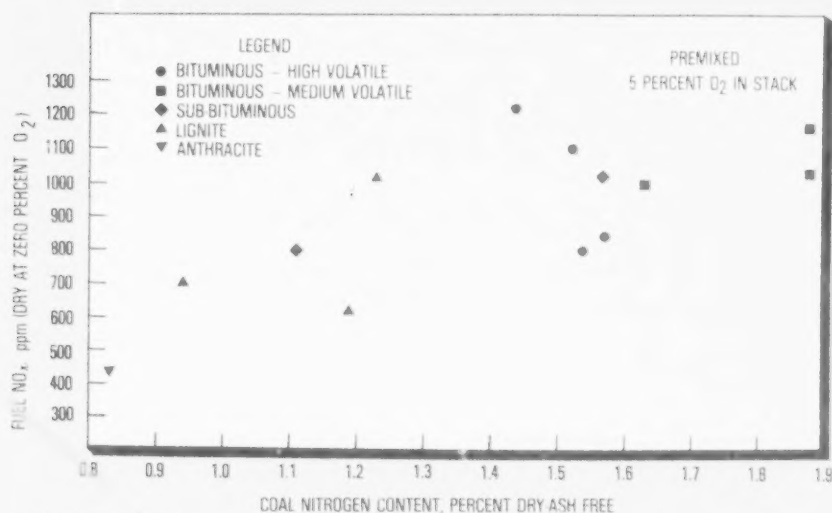


FIGURE 7—Effect of coal nitrogen on fuel NO_x

STAGED COMBUSTION

The primary interest is in the effect of fuel on the NO_x levels achievable under staged combustion conditions related to the low NO_x burner. The NO_x emissions as a function of nitrogen content are shown in Figure 8 for a fuel-rich premixed primary at the optimum stoichiometry. The overall stoichiometry is brought to 125 percent of theoretical air by the addition of secondary air at a fixed axial location. Under staged conditions the differences between coals are much smaller and NO_x emissions are between 300 and 400 ppm almost independent of the fuel nitrogen content. Both the two lignite (around 1.2 percent nitrogen) and the two bituminous coals (1.4 to 1.6 percent nitrogen) have retained their relative position although the absolute difference is less than 100 ppm. The absolute levels are also greater than those observed with the low NO_x burner (Figure 4). There are a number of factors that may account for this including: (a) effects of scale, (b) the premixed primary provides a less rich primary for the same burner stoichiometry due to mixing effects in the large burner, (c) the premixed primary stage does not have the distribution of stoichiometries which may lead to lower levels in the burner, and (d) the higher temperatures in the refractory lined system may affect both fuel devolatilization history and thermal NO_x formation. Limited tests show that a three-stage system with a very rich first stage (40 percent theoretical air), a less rich second stage (60 to 90 percent theoretical air) and a lean third stage (125 percent theoretical air) gives lower emissions than the two-stage system. It has also been shown that interstage cooling can decrease NO_x levels even further.

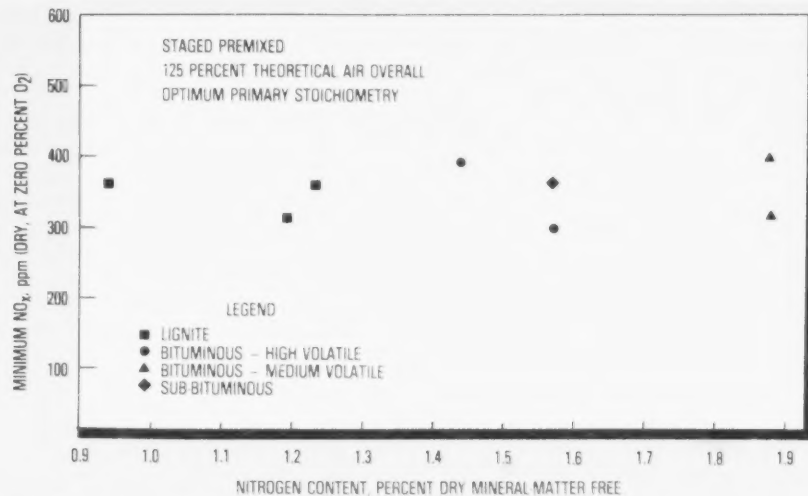


FIGURE 8—Achievable NO_x emissions in the small experimental facility

Overall, the fuel screening studies have been very valuable in identifying fuels with different emission potentials. From these results a smaller number of fuels are being selected for testing in the larger scale burners (3 to 35 thermal MW). If similar trends are shown to exist, the screening procedure will be established as a viable technique for low cost testing of specific fuels.

FIELD EVALUATION

Although the performance of the experimental burner is encouraging, to be of practical value, the burner must be evaluated on actual boilers operating over normal duty cycles. The evaluation must include not only emissions measurements but also system operability and thermal performance. Projects for this evaluation have been started for both industrial and utility boilers. The scope of both projects is virtually identical and the major difference is in boiler size and duty cycle. Industrial boilers are defined as ranging from 35 to 175 thermal MW (nominally equivalent to 100,000 to 500,000 lb of steam per hour); utility boilers are defined as going up to 300 electrical MW. The major tasks are as follows:

- The Program Definition Task provides for host boiler selection engineering design of a commercial prototype low NO_x burner, definition of the required measurement plan, and an overall program plan.
- The Burner Prototype Construction and Testing Task provides for construction of one prototype of the burner and testing in the large watertube simulator used in the burner development work. This testing will allow comparison of experimental burner results, optimization of conditions over the expected operating range, and resolution of mechanical problems. In addition, an example of the commercial burner from each host boiler will be tested in the large watertube simulator to provide a direct performance comparison.
- The Boiler Baseline Characterization Task provides for an analysis of the emission and thermal performance of each host boiler prior to modification as a basis of comparison. This includes operation over a wide range of conditions and with operating modifications to establish the minimum NO_x achievable.
- The Burner Installation Task provides for fabrication of the required number of burners, (see second task, above) and installation on each boiler. It also includes instrumentation for performance evaluation, corrosion panels at appropriate locations, and a TV camera for remote observation of the flame zone. Following installation, the boiler is to be operated over a range of conditions and an optimum operating point is to be established.
- The Long-Term Performance Evaluation Task provides for an 18-month test period over the normal boiler duty cycle. Gaseous species and selected thermal

MAJOR PROJECT TASKS

performance measurements will be made continuously, with three to five 30-day detailed evaluation periods equally spaced over the period.

- The Industry Coordination Task provides for a periodic review of the project status by interested parties, including manufacturers and users. This activity will be coordinated with the Technical Review Panel in the ongoing burner development activity.
- The Boiler Restoration Task provides for removal of the low NO_x burners and restoration of the host boiler to the initial configuration.
- The Data Analysis Task provides for an analysis of the data from the pilot scale study and a continual evaluation of performance during the field boiler operation. The goal is to generalize the results and allow a projection of burner performance in other systems with different fuels.
- The Design Approach Documentation Task will combine a factual summary of the experience on each boiler with the data analysis from the Data Analysis Task, above, to provide a general guide for application of the low NO_x burner to a wide range of boilers and fuels.

The industrial boiler project is being conducted by Energy and Environmental Research Corporation (EER) with Foster Wheeler Energy Corporation as a major subcontractor. The utility project is being performed by Babcock and Wilcox with a subcontract to EER. Both projects are scheduled for completion in late 1982.

CORROSION TESTING

Current new boilers over 73 thermal MW input, which are designed to meet the NSPS, incorporate staged combustion and/or improved burners in conjunction with the normal firing design. There has been mixed evidence for the existence or extent of accelerated waterwall corrosion with the fuel-rich conditions that may be produced in the lower part of the firebox. Therefore, a project has been initiated to fully evaluate these effects on four boilers of different firing configurations operating at or below the NSPS of 300 ng NO_x/J (0.7 lb $\text{NO}_x/10^6$ Btu). The evaluation of corrosion rates will include the use of both removable corrosion panels and ultrasonic tube thickness measurements before and after a 24-month operating period. Evaluation of emissions will include both continuous gaseous pollutant measurements and Level 1 analysis for potentially hazardous pollutants. This project will provide both a quantitative definition of any problem and identification of needed control approaches.

Three host units have been selected, one each manufactured by Combustion Engineering (CE) [410 electrical MW], Babcock and Wilcox (B&W) [450 MW], and Foster Wheeler [626 MW]. The fourth unit will be selected at a later date based on test results. Baseline emissions have been measured on two units (CE and B&W) and NO_x levels are at or below the pending revised NSPS. The corrosion panels will be installed on all three units during scheduled outages over the next year. If possible, part of the corrosion panels will be removed for analysis during another scheduled outage after one year and replaced with new panels which will subsequently be removed and analyzed.

STOKER BOILERS

The stoker boiler firing system can be used for commercial and industrial boilers in the range of 4 to 120 thermal MW; however, above approximately 40 MW, pulverized coal may be cost competitive. With the emphasis on increased use of coal for industrial steam generation, NO_x control for stoker-fired systems must be considered. The program covers field testing, a combustion modification program, and laboratory work. Each of these program areas is discussed below.

Under joint sponsorship of DOE and EPA, the American Boiler Manufacturers Association and KVB, Inc. are performing emission field testing on 10 stoker coal-fired boilers over a range of steam capacities and designs. Reports on the first two systems have been issued.

A contract is in negotiation to modify the firing system on five field operating boilers to provide for NO_x control. Two of the systems will be spreader stokers which

is the firing mode used in larger size boilers, while three will be of the mass feed type used in smaller boilers. Based on available information, the contractor will design the applicable control techniques and install the equipment on the boilers. Each boiler will be operated over a range of conditions to determine the optimum NO_x control achievable. Each boiler will be operated for a minimum of 30 days at its optimum condition and comprehensive emission testing will be performed.

LABORATORY WORK

While the work on practical boilers can provide valuable guidance for NO_x control by modification of current stoker designs, a better understanding of the pollutant formation processes is required to establish the approaches for the maximum achievable control for new designs. While the reaction of coal in the overthrow region of a spreader stoker appears to have some similarity to pulverized coal firing, the pollutant formation processes are not well understood due to both the larger coal size and the use of mass burning on a grate to complete the combustion. In the overthrow region the coal is devolatilized and partially reacted in the hot gases rising from the grate. The larger coal particles then fall on to the grate and burn in the mass mode with combustion air supplied from underneath. The smaller particles may be carried out of the combustion zone by the hot gases without ever reaching the grate.

A grant has recently been awarded to provide the required understanding of these combustion processes. The approach is to examine each region of the stoker separately, then to integrate the knowledge into a prototype system for testing. The overthrow region will be simulated with a small tower furnace where coal with particle sizes typical of spreader stokers will be reacted in either co- or counter flowing streams of hot gases. The temperature composition and stoichiometry of the gases will be varied to determine the effects on both sulfur and nitrogen specie evolution from the coal. Both the effluent gas and residual solids will be analyzed. The mass burning will be simulated with a fixed bed experiment where beds of various thickness will be burned under a variety of conditions. Based on the results of these experiments, a model stoker will be constructed to evaluate the combination of the two combustion modes in the optimum manner for a new stoker design.

TANGENTIALLY FIRED BOILERS

For boilers without NO_x control, tangentially fired boilers generally produce lower NO_x emissions than other firing methods; however, pilot scale data on the lowest achievable NO_x levels for tangential boilers are not available. In view of the pilot scale performance of the low NO_x burner for wall-fired boilers, a study has been initiated to generate that data. A pilot scale furnace will be used to study tangential firing at 0.5 to 1.0 thermal MW. Examination of the design approach and pictures of the fireball of a tangential unit suggests that at least two phenomena need to be studied.

First, the characteristic flame originating from each fuel injection elevation strongly resembles the axial diffusion flames studied by Heap, i.e., an axial fuel jet completely surrounded by a flame sheet. This configuration was shown to produce lower NO_x levels than more highly mixed swirl burners. It could be postulated that this factor accounts for the differences observed in practical boilers; however, a second possibility must also be considered. It can be argued from available photographs of a tangential fireball that, within a short distance, the flame from each corner begins to interact with other flames. It is well known that NO_x can be partially reduced on passage through a flame front. It has also been shown that NO added to the combustion air of a lean residual oil flame could be reduced by up to 35 percent. If the NO_x formed in one flame of a tangential unit is processed by another flame front, a similar reduction of NO_x might occur. It is obvious these two possibilities are not independent phenomena. The research program is structured to examine the effects of both initial fuel/air mixing and flame interactions independent of the entire fireball. The results will then be used to define experiments for the tangential configuration of the pilot scale furnace.

FLAME STUDIES

Although the individual flame in a tangential boiler may be compared with an axial diffusion flame from a circular symmetric swirl burner, there are some potentially important differences. The axial diffusion flame studied by Heap and others has the central fuel jet completely surrounded by combustion air; whereas, in the tangential burner the bulk of the combustion air is added asymmetrically from ducts above and

below the fuel jet. In addition, the axial diffusion flame is surrounded by, and entrains, relatively cool recirculated combustion gases; whereas, the tangential flame has relatively cool combustion gases on the waterwall side, relatively hot combustion gases from the center of the fireball, and very hot gases from the flames above and/or below. Therefore, while the initial experiments on burner design for air/fuel contacting control can be carried out under symmetrical conditions, considerations must be given to a series of experiments more closely simulating the asymmetric environment described above. These single flame experiments will be based on available information on axial diffusion flames and will be used to establish optimum configurations for control of NO_x formation in the early flame zone.

FLAME INTERACTION

A second series of experiments will be performed to examine the effect of flame interactions on emissions from various burner configurations. It may be postulated that the two important variables in flame interactions are the axial distance at which impingement occurs and the angle of impingement. The axial distance may be thought of as representing the extent of reaction of the coal jet. Close to the injector the bulk of the coal will be unreacted and the oxygen availability will be high. As the distance from the injector increases the fraction of the coal reacted will increase up to a point where all the volatile matter is evolved and the oxygen availability will decrease. The point of interaction of this flame with the combustion products of a second flame can be expected to have an influence on the NO_x reduction that will result. While it is not possible to predict the optimum point for a reduction of NO_x by the flame processing mechanism, it can be postulated that this point will occur before all of the volatiles are consumed and, therefore, where fuel intermediates (H_2 , CO , NH_3 , etc.) are available to reduce the NO_x . This point will also depend strongly on the character of the flame and may be more likely to occur if the flame is fuel rich overall. While the axis of the two adjacent fuel injectors on the same elevation is at 90° , the effect of the fireball appears to deflect the later portion of each flame from the injection axis, thereby decreasing the angle at which the adjacent flames interact. A change in this angle can be expected to influence the degree of interaction by affecting both the distance and the mixing processes of the two jets. None of the data currently available provide a basis for predicting these effects.

To examine the two phenomena discussed above, an experiment with two interacting flames will be conducted. Figure 9 shows a schematic of the experimental

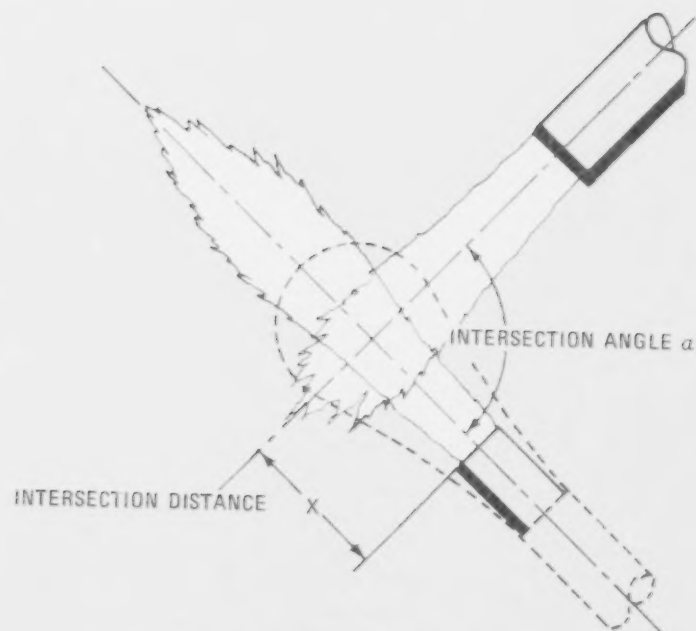


FIGURE 9—Sketch of flame interaction experiment concept

variables to be considered. A modification of the single burner extension of the furnace will provide for an evaluation of the effects of distance and angle for selected burner configurations.

The results of these two well-characterized experiments will be used to design concepts for testing in the tangential model of the EPA furnace.

HEAVY LIQUID FUELS

The experience in pilot scale development of staged combustion and advanced burner design indicates that it is more difficult to achieve high percentage reduction of NO_x for heavy liquid fuels than for coal. Some evidence exists to indicate that the difficulties may arise from differences in the way that the nitrogen is bound in the fuel and, therefore, the reaction history of the fuel nitrogen intermediates. More refractory nitrogen in the petroleum derived residual fuel oils may be released later in the combustion processes when more oxygen is available for conversion to NO_x . The synthetic liquids derived from coal and shale not only have larger amounts of nitrogen but also have the nitrogen distributed over the full boiling range of the crude. In addition, major limits on NO_x control for petroleum residual fuel oils is the onset of carbonaceous particulate (smoke) formation as the primary zone becomes fuel rich. Since the formation of carbonaceous particulate is related to the carbon-hydrogen ratio of the fuel, this limitation may become more severe for synthetic liquids derived from coal.

FUEL-SCREENING EXPERIMENT

A fuel screening experiment is in progress in an attempt to quantify the effects of fuel composition on both NO_x and carbon particulate emissions. A small furnace similar to the one shown in Figure 6 is used. The fuel is introduced through a sonic atomizer which produces a relatively narrow cut of small droplets ($20 \mu\text{m}$). The droplets are well dispersed in the combustion air stream, producing a mixture believed to be similar to the premixed coal burner discussed earlier. This system allows a rapid,

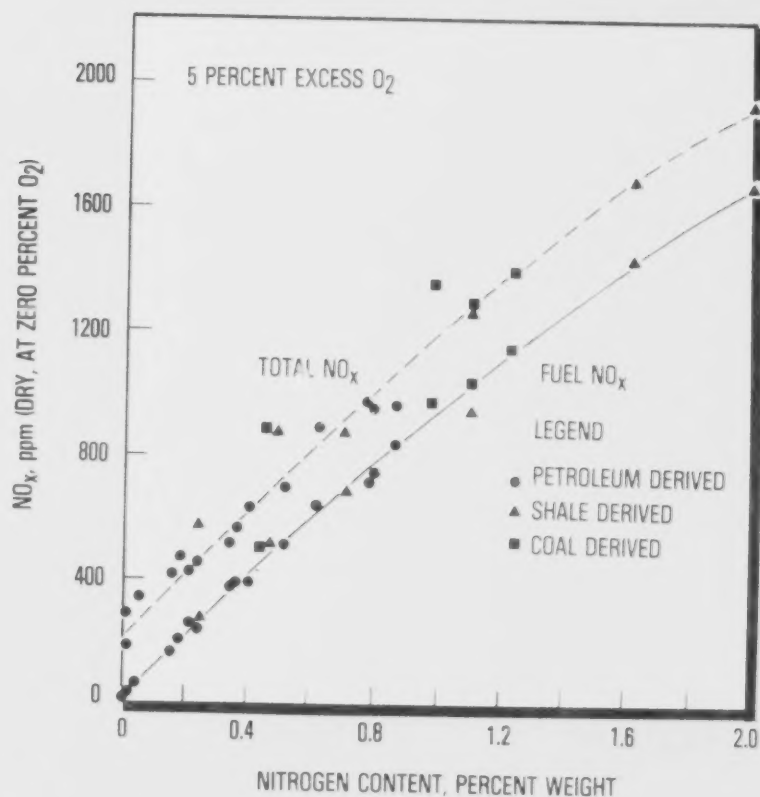


FIGURE 10— NO_x emissions from liquid fuels

NO_x EMISSIONS/NITROGEN CORRELATED

cost-effective screening of a wide range of fuels even when the availability is limited to small quantities, such as for many synthetics. The system can be run both staged and unstaged for an assessment of the emission formation and control potential.

The correlation of NO_x emissions with fuel nitrogen content is shown in Figure 10 for fuel lean conditions. The lower curve shows the fuel nitrogen conversion as determined by substituting an argon oxygen mixture for the combustion air. The fuel data for petroleum-, shale-, and coal-derived liquids show the same trend, that is, NO_x increasing with fuel nitrogen content and the fractional conversion decreasing with increasing nitrogen. This is similar to previous data for doped distillate oil and for limited petroleum residual testing. Considering the differences in the fuel sources and properties, it is remarkable that the trend is so consistent. It is also in marked contrast to the previously shown behavior for coals (Figure 7). The upper curve representing total NO_x, using air as the oxidizer, is drawn through the petroleum-derived fuel data up to 0.8 percent nitrogen and through synthetic fuel data at higher nitrogens. The difference between the two curves represents the thermal NO_x. The thermal NO_x for pure alternate fuel appears to be consistently higher than that for petroleum oils. (Some of the data shown for the synthetics are blends with petroleum residuals and these approach the petroleum line as the percentage synthetic decreases.) The reasons for this apparent difference have not been determined.

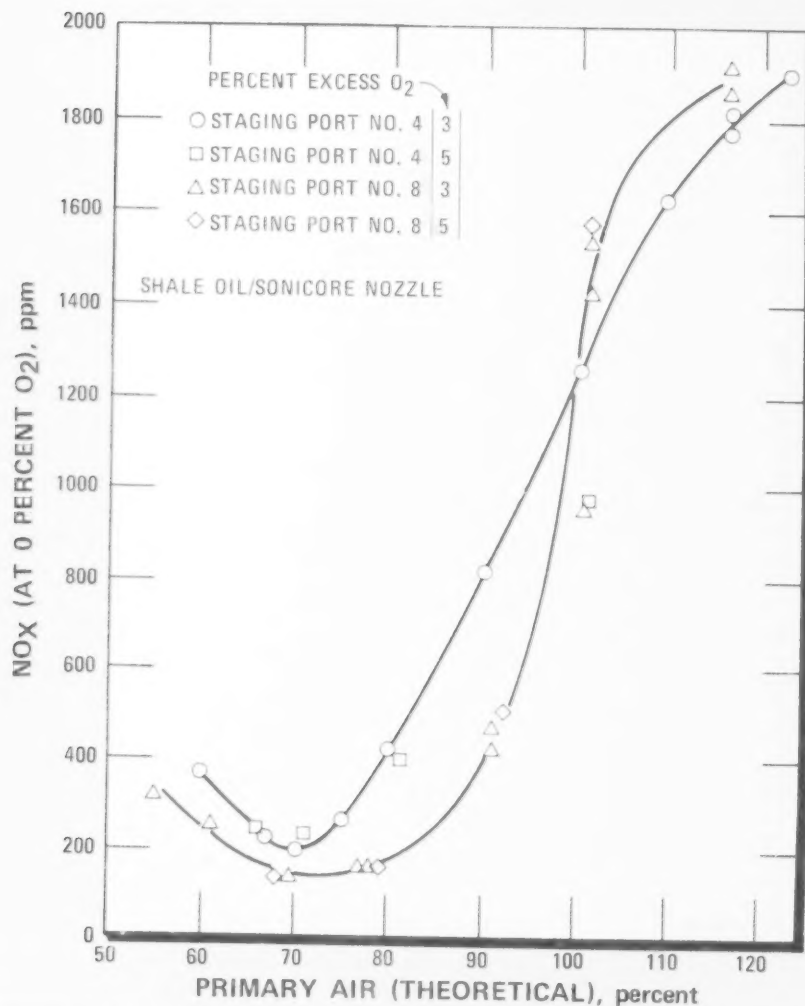


FIGURE 11—Effect of primary air on NO_x emissions for a crude Parahoe shale oil

STAGED CONDITIONS

These screening data have been used to select a limited number of fuels for testing under staged conditions. An example of the results obtained for a crude shale oil is shown in Figure 11 for two primary zone residence times. The primary air is introduced through the burner and secondary air to complete the combustion is introduced through ports at different downstream locations. In both cases emissions are reduced from about 1900 ppm to less than 200 ppm. The longer residence time gives a somewhat lower minimum over a broader range of primary rates, a characteristic shown in most staged combustion experiments. The minimum achievable NO_x emissions for a wide range of fuels are shown in Figure 12. The emissions for petroleum-derived fuels show a sharp rise as nitrogen content increases from zero to 0.6 percent, then the emissions for the synthetics exhibit nearly no increase as nitrogen content increases from 1.0 to 2.0 percent. The reason for the differences in staging effectiveness is believed to be related to the volatility of the fuel nitrogen as will be discussed later.

The closed symbols on Figure 12 show the emissions trend for fuels tested in a 1 MW thermal package boiler simulator using a similar sonic nozzle and axial air flow distribution to simulate the tunnel furnace. The emissions follow the same trend as the tunnel furnace; however, in general the NO_x levels are somewhat higher. The carbon particulate formation tendency of fuels under staged conditions has also been briefly studied in this system. At minimum NO_x , the smoke number for the crude shale was significantly lower than that for the petroleum oil tested. Sufficient quantities of coal-derived oils are not yet available for testing. These results show that the fuel screening technique is quite useful for indicating the performance of fuels in practical combustors.

GAS TURBINE ENGINES

The development of a low emission combustor technology for stationary gas turbine engines (SGTE) is nearing completion. The goals of this program were to identify and experimentally demonstrate (in full-size hardware) a new combustor concept capable of producing NO_x emissions less than 50 ppm on clean fuels and less than 100 ppm on fuels containing up to 0.5 percent chemically bound nitrogen without the use of water injection. These emission goals were to be achieved while maintaining very low CO and unburned hydrocarbon performance. The exclusion of water injection as a considered control approach derived from the efficiency penalty and operational problems associated with that technique while consideration of fuels containing bound nitrogen resulted from EPA's belief that SGTE's would need to burn dirtier fuels such as residual oil or synfuels if they were to attain a sizeable portion of the utility market.

The program was structured with a phased approach to include (a) identification of candidate design concepts, (b) bench scale experimental evaluation of the concepts, (c) selection of the most promising design approach, scaleup of the concept to the 25 MW size range and construction of full scale hardware, and (d) rig testing of the full scale hardware. In all, 29 concepts were evaluated on the bench scale. While a number of the concepts were capable of meeting the program goal on clean fuels, the only combustor concept capable of meeting the goals on both clean and nitrogen containing fuels was a configuration called the rich burn/quick quench concept shown in Figure 13. This configuration involves a premixed fuel and air stream issuing into a fuel rich primary zone. The combustor is then contracted at the point of secondary air addition to increase the rate of mixing between primary and secondary streams and to provide a quick transition from fuel rich to fuel lean stoichiometry, thereby minimizing thermal NO_x . Tertiary air ports are also provided to bring the exhaust to the overall fuel/air ratio for the required turbine inlet temperature.

BENCH SCALE COMBUSTOR

The performance of the bench scale combustor is shown in Figure 14. The shaded zone shows the range of primary zone combustor residence time typical of current generation stationary gas turbine engines. For both clean and nitrogen containing fuels (simulated with a pyridine doped distillate oil) the combustor exceeded the performance goals. CO emissions were well below the 100 ppm goal. For clean fuels the low NO_x and CO levels were readily achieved over the entire engine operating cycle. For dirty fuels it was necessary to maintain control over primary zone stoichiometry ($\phi=1.2$ to 1.5 or 82 to 67 percent of theoretical air) in order to achieve low emissions over the operating cycle. The problems associated with maintaining stoichiometry control (i.e., variable geometry) are significantly mitigated by the facts

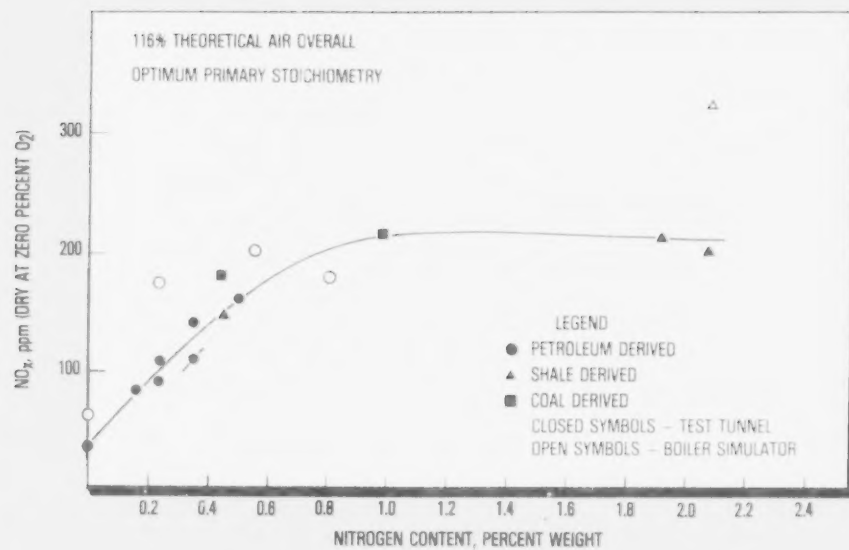


FIGURE 12—Minimum achievable NO_x for liquid fuels under staged combustion conditions

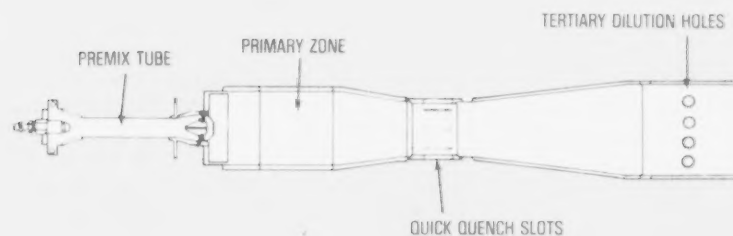


FIGURE 13—Low NO_x gas turbine combustor

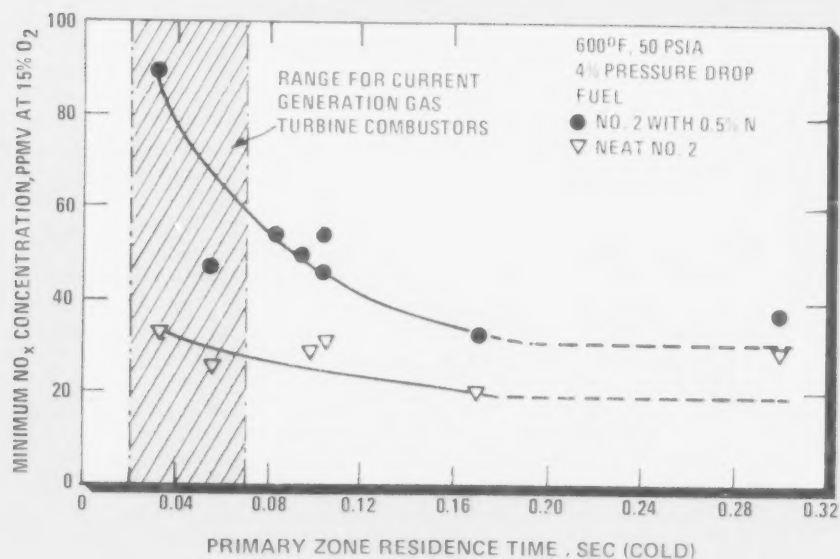


FIGURE 14—Gas turbine combustor performance

that control is only required for the primary zone, and only 10 to 20 percent of the total engine flow passes through the primary. A simple variable damper on the inlet to the premix tube has been shown to provide the required control at a reasonable pressure drop. At longer residence times, NO_x emissions were 20 ppm for clean fuels and 40 ppm for a 0.5 percent nitrogen doped fuel. In both cases these NO_x emissions are a factor of 2.5 less than the program goals. These results have implications for the potential of the combustor for new design stationary gas turbine engines where combustor residence time may not be a major constraint.

SCALED UP COMBUSTOR

This combustor concept was scaled up to a size commensurate with a single can from a multiple can 25 MW machine. Full scale rig testing of the hardware was performed and the results indicate a successful scaleup procedure. NO_x emissions less than 45 ppm were recorded for clean fuels while on dirty fuels the NO_x levels were around 75 ppm. These results are consistent with those for the bench scale combustor at the residence time used in the scaled up combustor (4 msec). Nitrogen containing fuels tested at full scale include a distillate cut shale oil containing 0.25 percent nitrogen and number 2 oil doped to 0.5 percent nitrogen as pyridine. Future plans call for examining the combustor on an SRC II fuel, a residual shale oil, and a petroleum-derived residual oil.

STATIONARY RECIPROCATING ENGINES

Stationary reciprocating engines are used both as compressor drives and for generation of electric power. The stationary engines are large bore, two- and four-cycle devices operating at relatively low speed as compared with automotive engines. Dependent on the fuel, the engines may be either diesel or spark ignition. While the NO_x control techniques developed for stationary continuous combustion systems are applicable in principle, the intermittent high pressure combustion processes in reciprocating engines present difficulties in application.

The goal of the reciprocating engine program is to achieve a 50 to 60 percent reduction in NO_x without increase in carbonaceous emissions and with a minimum impact on fuel efficiency. The initial concept screening has been completed and a prioritized list has been prepared for diesel and spark ignition categories. These concepts will be screened on laboratory engines and the most promising technique for each category will be tested on a full scale engine for a short period. Longer field test periods are planned for a subsequent program.

INTEGRATED RESIDENTIAL OIL FURNACE

The degree of control achievable with current oil- and gas-fired residential furnaces is limited by the relative lack of flexibility of operating conditions and by cost constraints. This class of equipment emits pollutants near ground level in populated areas during a limited period of the year (i.e., the heating season). In addition, it consumes a significant amount of energy, almost exclusively as clean fuels (e.g., gas and light oil). An integrated residential furnace has been developed which has the potential for significant NO_x control and for increased efficiency. The main features of the furnace are shown in Figure 15. The initial development was the burner head for retrofit to existing furnaces which achieved a 15 to 30 percent NO_x reduction. It was also shown that matching the burner head with a new firebox could produce much larger NO_x reductions (e.g., 75 percent). As a result quantitative matching criteria were developed including (a) 25 percent heat removal from the firebox to minimize NO_x emissions, (b) chamber dimensions for minimum carbonaceous emissions and excess air requirements, (c) provision of the thermal mass to achieve a minimum firebox temperature of 333K for clean ignition, and (d) tunnel firing preferable to side firing.

WARM AIR DESIGN

The best system to achieve the criteria standards is a hydronic furnace; however, the bulk of the population are side fired warm air furnaces. Therefore, a warm air design embodying the criteria was developed using a finned metal firebox, as shown in Figure 15. The combination also allowed firing at a low excess air (20 percent) and minimum stack temperature for maximum efficiency during the operating cycle. In addition, two other features were designed into the furnace to maximize overall system efficiency. The burner draft damper prevents flow of air through the firebox when the burner is not firing, thereby reducing the off-cycle heat losses to the flue. The sealed air system provides outside air for both combustion and barometric draft

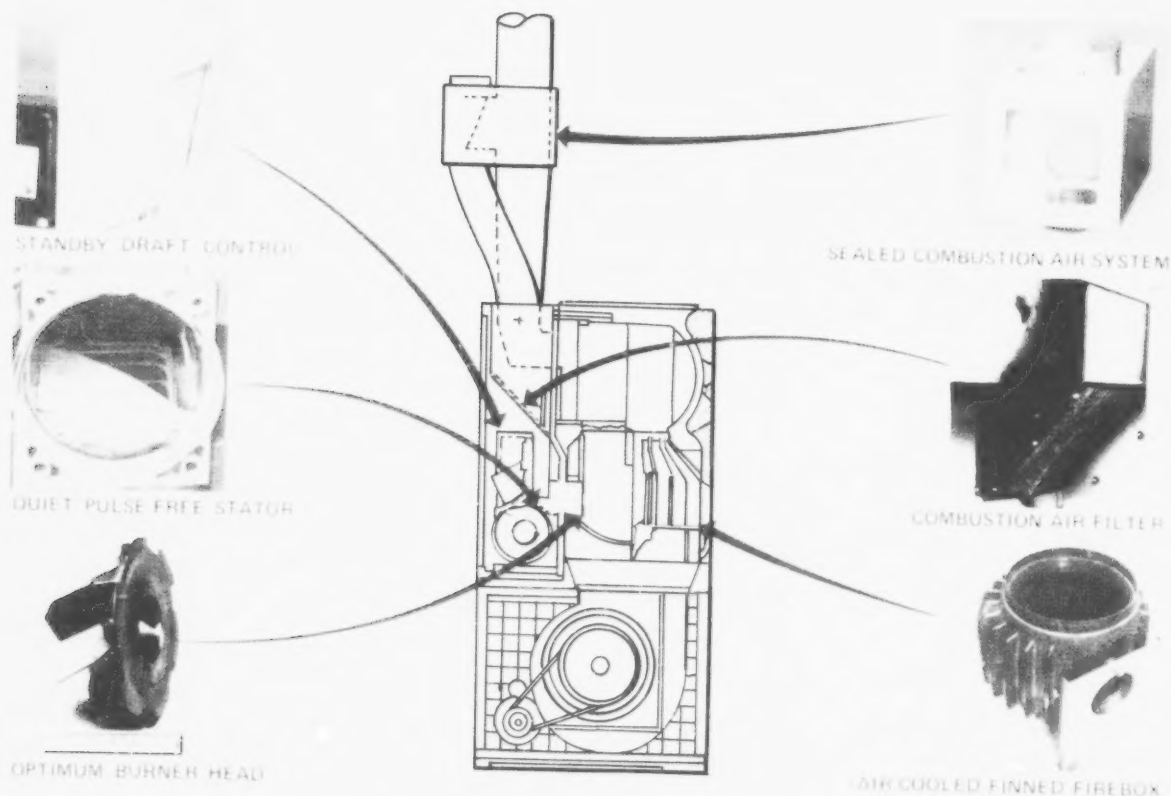


FIGURE 15—Low emission integrated furnace components.

HOST RESIDENTIAL FURNACES

control. This eliminates the use of conditioned air for these purposes and, thereby, should reduce infiltration of air into the house. The prototype was tested in the laboratory and produced a 65 percent reduction in NO_x relative to the existing furnace population with no increase in carbonaceous emissions. It was estimated that the furnace concept should result in about a 10 percent increase in thermal efficiency relative to the unmodified furnace.

Six furnaces were constructed and installed in host residences, three in Albany, N. Y., and three in Boston, Mass. The furnaces have been operated under normal duty cycles for two heating seasons (1977-79) and have performed satisfactorily. The emission performance has been equal to or better than the laboratory prototype for most of the period; however, in the mid-winter some lower quality oil containing sludge and greater amounts of fuel nitrogen resulted in some off-specification emissions. During the evaluation period, the efficiency of the furnaces was measured in several ways. The most rigorous measurement was cycle average efficiency which was based on total fuel input and warm air output over a total of three months for each furnace. This method, which measures useful heat delivered to the host residence, averaged nearly 75 percent over the first heating season. A strong correlation of efficiency for any given cycle and the fraction of the cycle time the burner was firing was developed. In addition, the fuel use for the test period was compared to the prior fuel deliveries to the residence. Since the thermostat was not controlled during either period and the fuel history was somewhat difficult to reconstruct accurately, the comparison should not be taken literally. Fuel savings of over 20 percent were observed for several furnaces and are believed to be essentially accurate. Overall the

integrated residential furnace has shown the potential for significant emission reductions coupled with increased efficiency.

ADVANCED CONCEPTS

The programs discussed above involve modifications to conventional combustion equipment to achieve NO_x reductions. There are some indications that the very nature of diffusion flame combustors may place some lower limit on the achievable NO_x emissions. Since there may be situations where even lower emissions are required, a number of advanced concepts are being examined. Many of these are combustion processes based on modifications of conventional combustors or on novel design. In addition, there are add-on treatment processes being pursued to achieve high removal efficiencies as supplements to combustion modification. Three of these are described below.

CATALYTIC COMBUSTION

One advanced concept that appears capable of achieving very low pollutant levels is catalytic combustion in which a catalyst is used in place of a diffusion flame burner to achieve the major energy release in a combustion system. The initial applicability is to clean gaseous and vaporizable liquid fuels as a premixed fuel and air stream must be presented to the catalyst. Oxidation of the fuel through both heterogeneous surface reactions and homogeneous gas phase reactions occurs within the channels of the catalyst bed at essentially adiabatic temperature. Complete combustion can be achieved at very short residence time and with very high volumetric heat release rates. The two apparent limits are (a) the temperature at which catalyst degradation becomes significant, and (b) the well known kinetic threshold temperature above which the rate of thermal NO_x formation becomes significant. Therefore the application of the technology to stationary combustion sources requires new system designs to achieve long life and high thermal efficiency.

The graded cell catalyst has been developed during the program and patented. This concept uses large cells at the inlet end of the catalyst monolith to maintain heterogeneous ignition at very high fuel throughput (space velocity) with progressively smaller cells to complete the fuel oxidation. This concept has been tested versus a conventional straight cell catalyst of the same formulation. The graded cell catalyst achieved three times the volumetric energy release of the straight cell and had a much more uniform axial temperature profile. In addition, other versions of the graded cell have shown extremely high heat release capability ($>10^8$ Btu/hr/ft³/ATM) and low thermal NO_x (<50 ppm at 1700°C). The graded cell catalyst appears to be a major improvement in combustion catalyst technology.

FUEL NITROGEN CONVERSION

There has also been significant progress in the development of systems for application of catalytic combustion to boilers burning nitrogen containing fuels. A catalytic staged combustor has been designed and tested, using the configuration shown in Figure 16. The first-stage bed is run fuel rich to partially oxidize the fuel and to promote formation of N_2 from fuel nitrogen compounds. Heat is removed between stages to reduce the adiabatic temperature in the second stage. Then the balance of the air is added and the fuel oxidation is completed in the second stage catalyst. This configuration allows the overall system to operate at minimum excess air for high efficiency without exceeding the allowable temperature in either catalyst bed. The conversion of fuel nitrogen to NO_x is shown in Figure 17. The first stage was operated at three levels of theoretical air (50 percent, 60 percent, and 70 percent) while the overall theoretical air was varied from 60 percent to 150 percent. With 50 percent first-stage air, the oxidizable nitrogen levels ($\Sigma\text{XN}=\text{HCN}+\text{NH}_3+\text{NO}$) were relatively insensitive to the overall air with a weak minimum below 30 percent conversion around 100 percent theoretical air. When the primary was operated at a more optimum condition (60 percent to 70 percent theoretical air) the ΣXN decreased to below 10 percent. Other studies of fuel nitrogen conversion show that the level attainable is strongly dependent on the catalyst as well as the operating conditions. Low thermal NO_x coupled with minimum fuel nitrogen conversions make catalytic combustion an attractive technique where very low emissions are required. Development of improved catalyst and auxiliary system components is in progress. These components will be integrated into several prototype systems for laboratory evaluation of the performance of catalytic combustion in various applications.

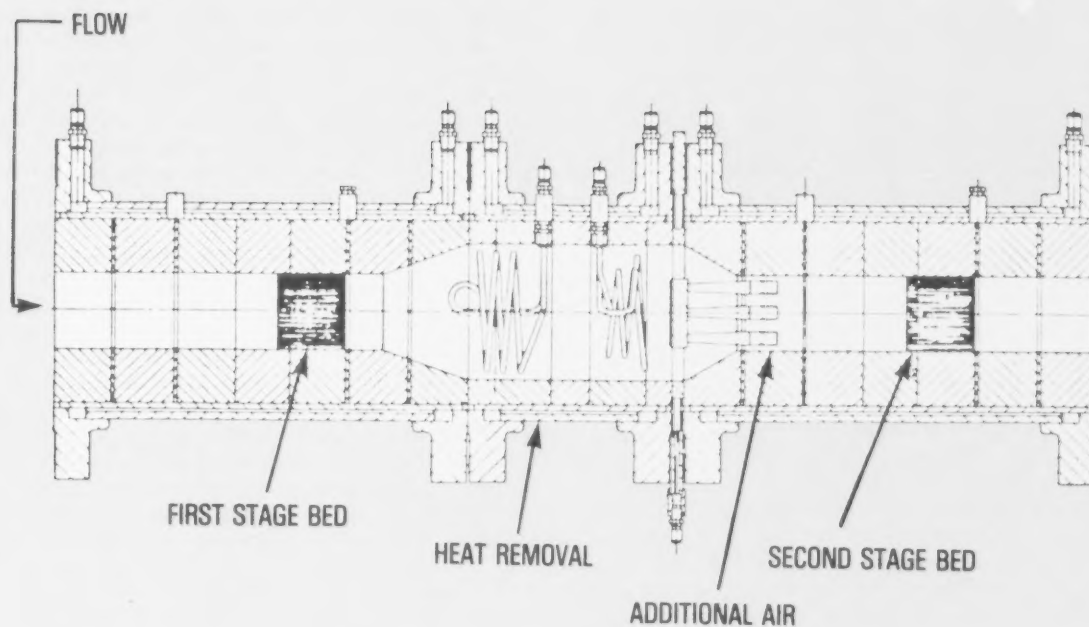


FIGURE 16—Catalytic staged combustor

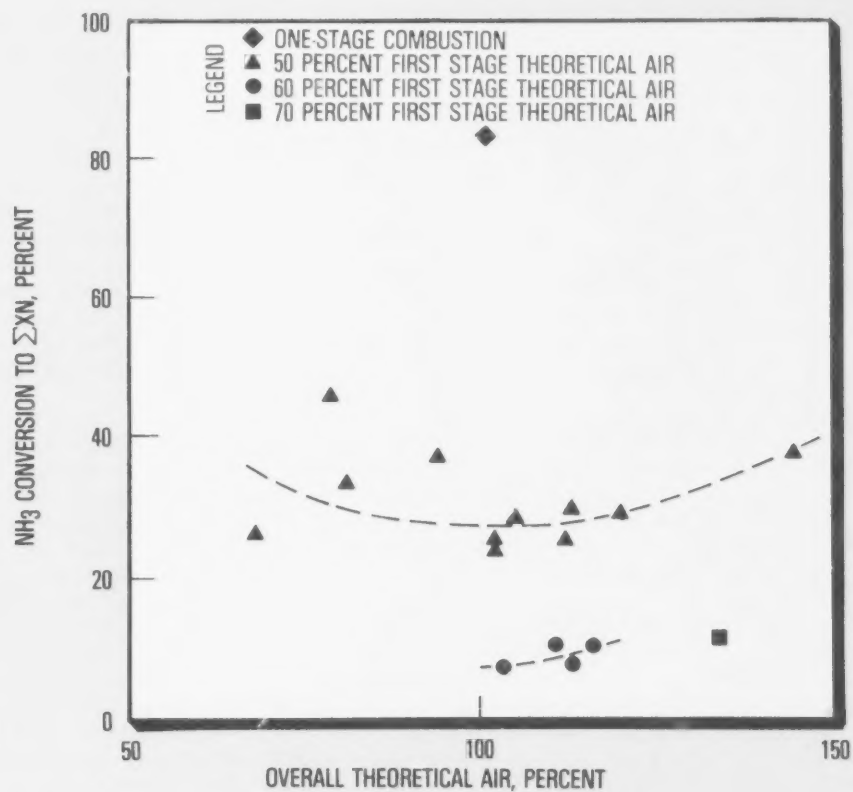


FIGURE 17—Fuel nitrogen conversion staged

HOMOGENEOUS REDUCTION

The homogeneous noncatalytic selective reduction of NO_x with NH_3 occurs in the presence of oxygen at temperatures around 1300K. The temperature window can be lowered by the addition of hydrogen. This technique is a proprietary process that has been evaluated in oil- and gas-fired systems both in the laboratory and in field operating boilers. NO_x reductions from 40 to 60 percent have been reported for practical systems. The EPA has conducted an analysis of the potential applicability of the process as a supplement to combustion modification in coal-fired boilers. The system requires a manifold for injection of NH_3/H_2 /carrier streams into the boiler volume at the appropriate temperature window (normally in the superheater region). Laboratory tests have shown 40 percent to 60 percent reduction in a coal-fired system using practical NH_3 levels. The main problem areas are (a) achieving uniform injection, (b) maintaining the injection in the proper temperature window during load swings, (c) ammonium sulfate deposition on convective surfaces, and (d) significant capital and operating costs. The technique appears to be a potentially useful supplement to combustion modification in Air Quality Control Regions where very stringent control may be required.

FLUE GAS TREATMENT

In May 1978, two programs were initiated for the development of NO_x flue gas treatment for coal-fired systems. One program is for NO_x control using Hitachi Zosen's process which is based on selective catalytic reduction of NO_x with NH_3 . The process utilizes a metallic honeycomb catalyst arrangement for coal-fired applications. The reactor is located between the boiler economizer and the air preheater and in front of any particulate control device. The reaction temperature is in the range of 350°C to 420°C. The pressure drop is about 200-500 Pa. For 90 percent NO_x reduction, a $\text{NH}_3:\text{NO}$ mole ratio of 1:1 is used. The process will be evaluated in a 2000 Nm^3/hr (0.5 electrical MW) pilot plant scale coal-fired source. The host site for the pilot plant will be Georgia Power Company's Plant Mitchell near Albany, Georgia. Flue gas will be obtained from Unit 3, a pulverized coal-fired Combustion Engineering boiler with a nameplate rating of 125 MW.

EVALUATING UOP-SHELL

The second program for simultaneous SO_2/NO_x control is evaluating the UOP-Shell process. Briefly, the process employs two or more parallel passage reactors using CuO as the sorbent for SO_2 and using CuSO_4 as the catalyst for the reduction of NO_x with NH_3 . A multiple reactor arrangement is needed to allow regeneration of CuSO_4 to CuO . Hydrogen is used as the reductant. The reactors are located between the boiler economizer and the air preheater and in front of any particulate control device. The process operates at a temperature of 400°C during both acceptance and regeneration cycles. The cycles will be controlled for 90 percent removal of both NO_x and SO_2 . For 90 percent NO_x reduction, a $\text{NH}_3:\text{NO}$ mole ratio of 1:1 is used. The process also will be evaluated in a 2000 Nm^3/hr pilot plant coal-fired source. An existing pilot plant, previously used by UOP to evaluate SO_2 removal, will be modified for simultaneous removal of NO_x and SO_2 . The host site for the pilot plant will be Tampa Electric Company's Big Bend Station in North Ruskin, Florida. Flue gas can be obtained from Unit 1 or 2 which are Riley-Stoker pulverized coal-fired boilers with a nameplate rating of 400 MW each.

TVA has performed a preliminary economic evaluation of NO_x and NO_x/SO_x flue gas treatment processes for EPA. The base case was a new, 500 MW power plant burning 3.5 percent sulfur coal and emitting 600 ppm NO_x in the flue gas. The total capital investments and annual revenue requirements for three dry NO_x (selective catalytic reduction) removal processes ranged from \$32/kW and 1.9 mills/kWh to 3.4 mills/kWh, respectively. A dry process for simultaneous removal of both SO_2 and NO_x (UOP-Shell) had a capital cost of \$132/kW and an annual revenue requirement of 6.3 mills/kWh.

FUNDAMENTAL COMBUSTION RESEARCH

The fundamental combustion research (FCR) program provides a synthesis of the understanding of basic combustion phenomena in the context of practical combustion systems. A number of aspects of the problem are currently being studied. To place the FCR program in proper perspective, it is important to understand the relationship between FCR and the more hardware-oriented technology development efforts being pursued by Combustion Research Branch (CRB). The hardware-oriented technology is based on current understandings of the complex interactions between flame chemistry, combustion fluid mechanics and the physical/chemical properties of fuels. The

current level of understanding has proven sufficient to allow major advances in development of control technology hardware. The various FCR activities are coupled to the hardware development efforts through their focus on the key aspects of flame chemistry, combustion aerodynamics and fuel processing.

GAS PHASE REACTIONS

A major focus of the program has been on developing a set of chemical kinetic mechanisms to describe pollutant formation through gas phase reactions. The developed reaction set has been checked against a wide variety of reactor experimental results and is being used in what are termed limit case studies. Limit case studies significantly simplify furnace aerodynamics by describing the flow field as combinations of well stirred and plug flow reactors. By parametrically varying inlet conditions, process variables, and reactor sequencing (i.e., inlet stoichiometry, heat removal, etc.), such numerical studies help to identify the lower bounds of NO_x control which are set by the gas phase chemistry. These predictions can serve as a standard for judging the effectiveness of developed control techniques and can suggest various modifications of emerging control techniques to increase the effectiveness or range of applicability.

CHAR/NO REDUCTION STUDIES

The primary fuels of concern to EPA (in all phases of the program) are coal and heavy fuel oils, including synfuels. A number of efforts within the FCR program are addressing particular aspects of burning these fuels. MIT and Institut Francais du Petrole have shown that coal char and soot (respectively) may play an important role in determining exhaust NO_x levels from furnaces and boilers. It has been shown that both char and soot react with NO , even at low temperatures, and that such reactions may represent an important step in determining exhaust NO levels and may even be utilized to gain a significant level of emission control. MIT has applied for a patent based on their EPA-sponsored studies of char/ NO reduction.

Other studies are also being pursued to determine the rate of evolution and fate of nitrogenous species as they evolve from coal particles or oil droplets. Results from these studies are being directly used in the development of new low emission burners, particularly heavy oil burners for package boilers. Identification of primary pyrolysis products and speciation of secondary pyrolysis products may be the key to explaining variations in the effectiveness of staged combustion as physical characteristics of fuels are needed. An example of this is shown in Figure 18 where the achievable NO_x reduction with staged combustion is plotted versus a defined fuel nitrogen volatility. The volatility is based on the fraction of the fuel nitrogen in the original fuel that could be evolved as HCN during inert pyrolysis at 1373K. The highest HCN yield was

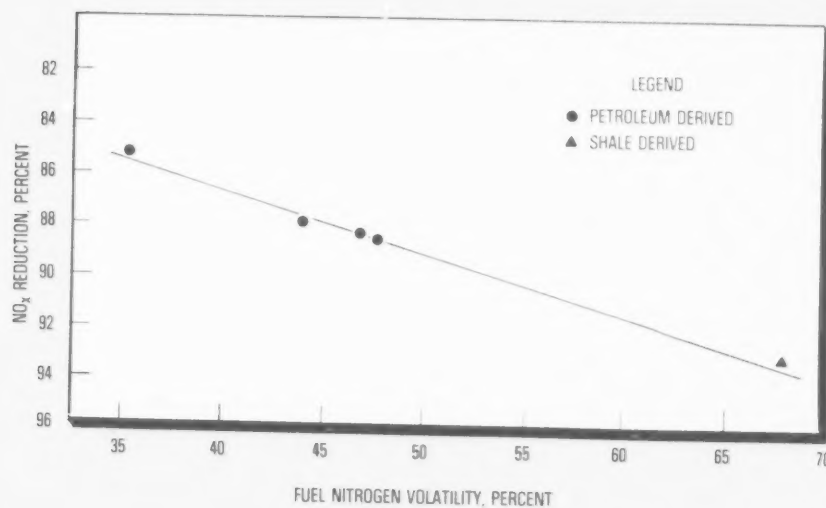


FIGURE 18—Staging efficiency and fuel nitrogen volatility

ENVIRONMENTAL ASSESSMENT

TEST RESULTS

from the crude shale oil which gave a 93 percent reduction under staged-combustion conditions. The reductions achievable from petroleum oils decreased as the fuel nitrogen volatility decreased. Although the data are limited, this graph shows the potential for correlation of the previously presented pilot scale data (Figure 12) with results of fundamental experiments.

Several additional studies are being pursued to investigate aspects of furnace aerodynamics. Turbulence, fuel ballistics, and numerical analysis of boiler type flow fields are being considered. By incorporating the aerodynamics, gas phase chemistry, and fuel chemistry studies into an integrated program package, significant input is being made to development of emerging control technology and suggestions are forthcoming on approaches to realizing advanced pollution control techniques.

The project for environmental assessment of NO_x control technologies has continued to evaluate all aspects of the problem associated with the application of combustion modifications for the control of NO_x emissions from stationary combustion sources. The primary emphasis of this work has been the evaluation of the environmental, economic, energy, and engineering implications of low NO_x combustion modification technology in order to provide comparisons with the environmental impact of baseline (uncontrolled) operation.

Testing of seven combustion sources has been carried out using EPA's IERL-RTP Levels 1 and 2 procedures for sample collection and analysis. The sources selected for comprehensive testing included a 180 MW tangential coal-fired utility boiler, a 500 MW horizontally-opposed coal-fired utility boiler, a 740 MW opposed-wall oil-fired utility boiler, two industrial stoker coal-fired watertube boilers, a blue flame oil-fired warm air furnace, and a 60 MW oil-fired gas turbine.

Individual test reports are being prepared for each test site. Results for the 180 MW utility boiler showed that burners out of service and biased firing (staged combustion modification techniques) yielded NO_x reductions of about 37 percent and 30 percent, respectively, compared with the baseline level (490 ppm @ 3 percent O_2 dry). A summary of the data is shown in Table 3. A slight increase in boiler efficiency was observed and was attributed to lower excess air levels. Analysis of the results led to the conclusion that the flue gas stream from this series of tests dominated the environmental impact. Sulfur dioxide and NO_x were the most significant gaseous species and potentially hazardous levels of arsenic, barium, beryllium, iron and sulfur were present. The solid effluents were estimated to be 1000 times less hazardous than the gaseous effluents. The NO_x controls employed were generally beneficial in reducing the flue gas environmental impact since most species were either reduced or unaffected. Slight increases were observed for nitrogen-containing (e.g., NH_3) and chloride species. There was negligible impact associated with the combustion modifications on the composition of the solid streams.

Detailed analyses on the other units tested are in progress. However, based on overall considerations of the potential for adverse environmental impact, coal-fired boilers have the highest priority for improved control for stationary combustion sources.

TABLE 3
Environmental assessment 180 MW_e coal fired utility boiler

Condition	Emissions		
	NO_x , ppm	CO, ppm	Particulate $\mu\text{G}/\text{J}$
Baseline	490	29	1.935
BOOS*	308	27	1.787
BIAS†	338	30	1.311

* Burners out of service

† Biased firing

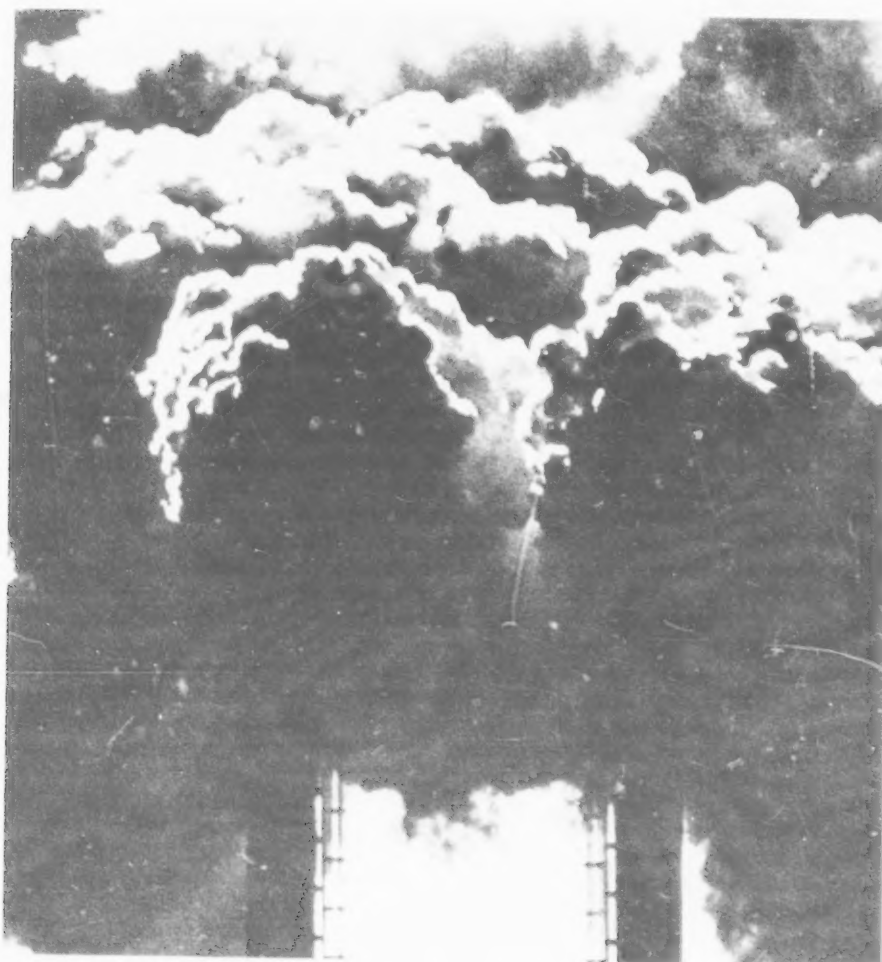
SUMMARY

The status of EPA's NO_x control technology development program can be summarized as follows:

- Based on projected fuel trends, NO_x emissions may increase significantly with current technology.
- More effective stationary source control technology can provide a means of mitigating this emission trend.
- The combustion modification techniques under development offer the potential for achieving significant NO_x reductions without adverse effects on other pollutants.
- These high levels of control can also be achieved at relatively low cost and without degradation of thermal efficiency.
- If extremely low levels of NO_x are required, advanced combustion technology and supplemental techniques such as ammonia injection and flue gas treatment are also under development.

ACKNOWLEDGMENTS

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questions & answers

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QUESTION

NO_x makes your eyes burn, but sulfur oxide can kill you. There seems to be equally large artillery focused on both, however. What are the comparative levels of effort on the two in your work?

RESPONSE: Mr. Frank T. Princiotta (EPA)

There is a difference in maturity between the two technologies. There are orders for about 60,000 megawatts of flue gas desulfurization systems. Many vendors offer technologies that meet current and projected sulfur oxide standards. That is not to say that more work is not needed. Clearly, in the areas of reliability and waste disposal, improvements are appropriate.

For nitrogen oxide, however, there are no meaningful regulations, particularly for stationary sources. This is true primarily because most of the regulations, such as the New Source Performance Standards, are based on technology, and frankly, there is no effective technology for nitrogen oxide today. This is a major thrust of the Research Triangle Park Nitrogen Oxide Control Program.

The question of relative environmental damage from sulfur oxide and nitrogen oxide is a difficult one. EPA, in the Clean Air Amendments of 1970, identified the criteria pollutants, those pollutants for which there were health data, suggesting that there are health and welfare damages associated with these pollutants above a certain ambient or air concentration. These criteria pollutants include nitrogen oxide and photochemical oxidants, of which nitrogen oxide is a precursor. The importance of nitrogen compounds as components of acid rain is expected to increase over the next 10 to 20 years. There is evidence that nitrogen oxide can damage the lung. Because of this and the fact that it is one of the precursors of photochemical smog, we are concerned. EPA is now in the final stages of considering a more stringent ambient nitrogen oxide standard

related to short-term exposure. Quite a bit of data indicate that high-level, short-term exposure to NO₂ is particularly deleterious to lung function. There is a good chance that a relatively stringent standard will be set. A body of health data suggests that NO₂, alone is a primary problem.

QUESTION

The throw-away SO₂ systems were more or less bypassed in this discussion. Has there been any recent development in these systems other than the use of soda, ash, and caustic soda, particularly in relation to disposal products and landfill?

RESPONSE: Mr. Michael A. Maxwell (EPA)

Forced oxidation is aimed directly at improving the disposal properties of the throw-away processes. The gypsum produced is a much more desirable end product because of its ultimate settled solids, its chemical oxygen demand, the probability that it can be landfilled, and the probability that it can be stacked similar to gypsum from the phosphate industry. In addition, over the last several years, there has been much work on commercial fixation processes whereby the sludge is stabilized or fixed with either fly ash or an additive such as lime. Yes, there has been quite a bit of work in waste disposal characterization and improvement. In fact, other than improvements in performance and reliability, this has been the primary emphasis in the throw-away program. The dual alkali method is an additional throw-away process involving soluble sodium scrubbing. It provides a calcium sulfite product for disposal similar to the lime and limestone system.





Leslie E. Sparks, Ph.D.

NEW DEVELOPMENTS IN FINE PARTICLE CONTROL

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PARTICULATE COLLECTION DEVICES

Particulate emissions are usually collected from an industrial smoke stack by one or more types of three conventional devices: fabric filters, wet scrubbers, and electrostatic precipitators (ESP). The design of each of these three devices has until recently remained relatively unchanged since the turn of the century. In recent years because of the need to collect smaller and smaller particles, meaning higher and higher collection efficiencies, many improvements have been developed for the conventional devices, and a number of novel devices and/or concepts have been proposed, developed, and/or marketed.

As the requirement to collect finer and finer particulate has been imposed, the cost of conventional particulate control has risen. Since many important collection mechanisms become much less effective on fine particles (particles less than 1.3 μm in diameter), conventional devices (with the exception of fabric filters) have become larger or have required more energy to operate and thus have become more expensive. In order to minimize the impact of these increased costs on our national clean air policy, the Environmental Protection Agency (EPA) has supported a research and development (R&D) effort aimed at (1) developing and demonstrating improvements to reduce the cost and increase the efficiency of conventional devices, (2) solving special particulate control problems having wide national implementations, such as those associated with the use of low sulfur coal and the increased use of diesel powered autos, (3) evaluating existing novel devices, and (4) discovering and bringing to a commercial feasibility stage devices based on new collection principles or concepts of new combinations of existing concepts.

PATB R&D SUBDIVISIONS

The Particulate Technology Branch (PATB) of EPA's Industrial Environmental Research Laboratory, located at Research Triangle Park, North Carolina, for the past 5 years has had the major responsibility for carrying out the R&D effort mentioned

above. Listed below are the currently most active and perhaps most important subdivisions of this particulate R&D program:

- Development of Technology for Control of Particulate Emissions From the Combustion of Low Sulfur Coal (Electrostatic Precipitators, Fabric Filtration, and Flue Gas Conditioning).
- Fugitive Emission Control for Particulate Sources.
- Development and Transfer of Particulate Control Techniques to Mobile Diesel Emissions.
- Determination of Emission Factors for Inhalable Particulate Ambient Standard.
- New Idea Identification and Evaluation (Novel Device Evaluation).
- New Particulate Control Technology Development (Novel Concepts).

In a two-stage ESP, particle charging occurs principally in the first stage, or precharger, where electric current densities are high. Particle collection occurs in the second stage, or collector, which would be designed to operate at relatively low current density and high electric field strength. Thus, it is in the precharger that back-corona caused by high electrical resistivity poses the greatest difficulty. The EPA/SoRI precharger differs from other prechargers under development because back-corona effects are overcome by electrical means and no special effort is made to keep high resistivity dust from collecting in the precharger. The decision to overcome high resistivity effects was made after laboratory experiments showed that a monolayer of high resistivity dust was sufficient to defeat the purpose of the precharger (1).

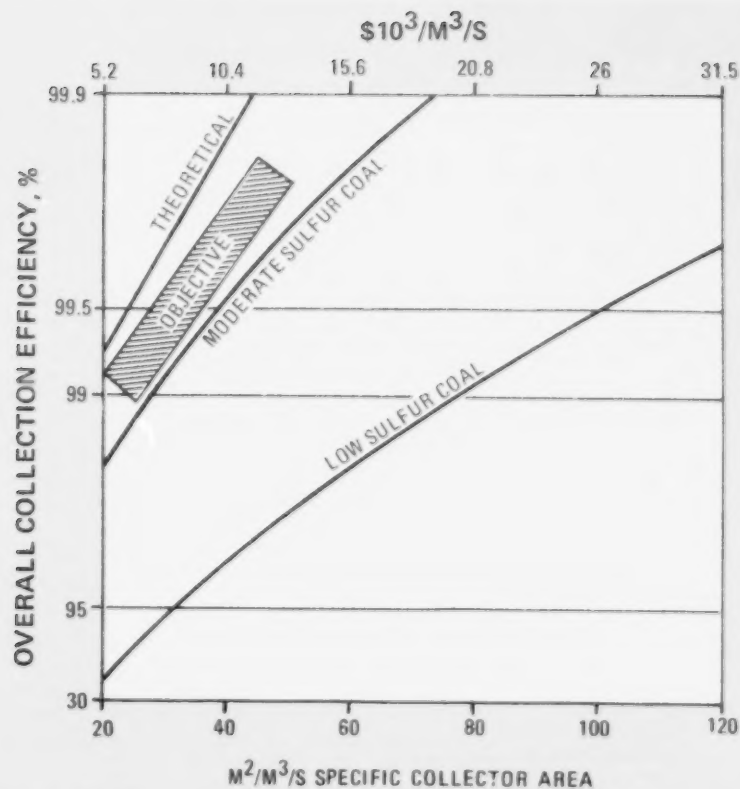
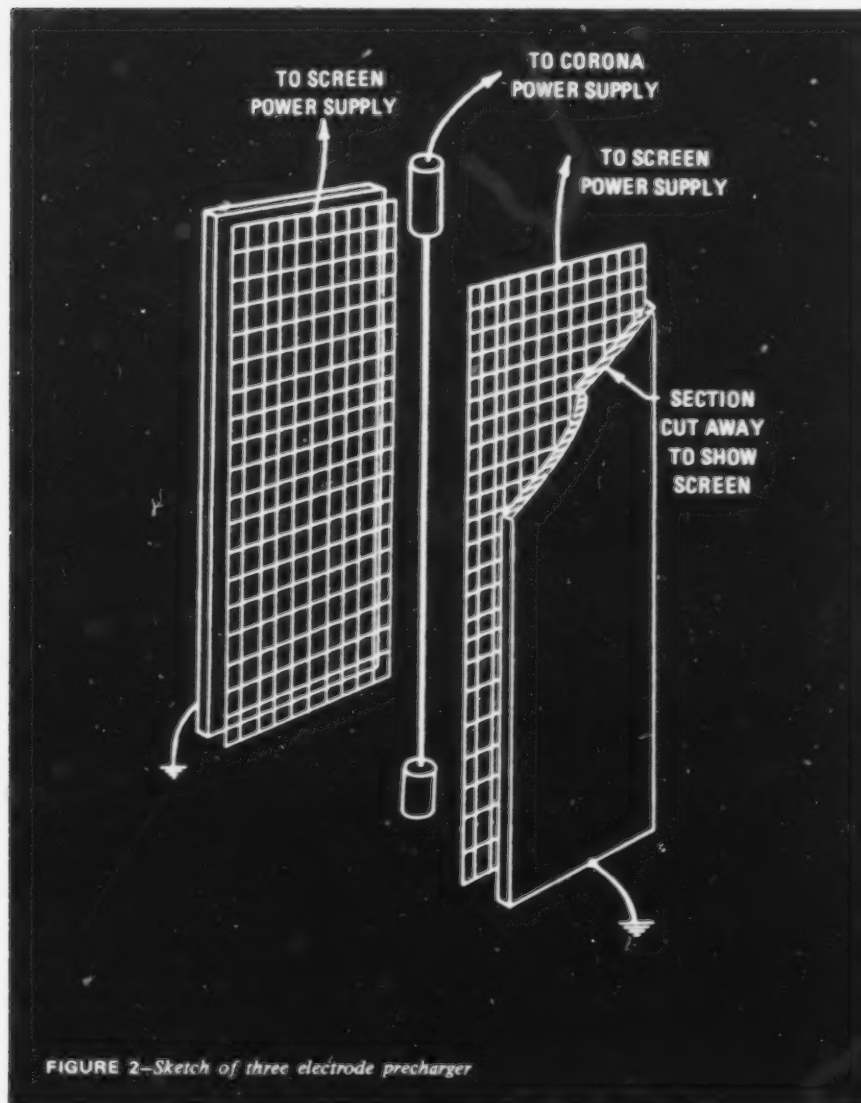


FIGURE 1—Efficiency versus estimated size and capital cost of electrostatic precipitators

SUPPRESSION OF BACK-CORONA

The precharger design for suppression of back-corona is based on a simple wire-plate electrode geometry, with the addition of perforated screen electrodes parallel to the plates, as illustrated in Figure 2. A high voltage applied to the corona wire will bring about corona conduction. In general, part of the current will go to the plate and part to the screen, depending on the relative potential at each. If the plate is grounded and the screen is set at a potential having the same polarity as that of the corona wire, ions moving toward the plate will be repelled from the screen. If the magnitude of the potential at the screen is great enough, the screen current may go to zero, while a considerable corona current passes through the openings in the screen, proceeding from the corona wire to the plate. If a high resistivity dust is introduced into the system, some of the dust may be precipitated on the plate electrodes. Very little dust will be deposited on the screen, because the charge on the particles will be the same as that of the screen, and hence there will be a repulsive force between the particles and the screen electrodes. If enough dust builds up on the plate electrode, back-corona may occur. The ions resulting from back-corona will have polarity opposite from that of the screen, so that in moving away from the plate they will be attracted by the screen and captured. Thus, the ion density in the space bounded by the screen electrodes can remain



NONOPTIMUM COLLECTOR STAGE

essentially unipolar, even if a substantial amount of back-corona activity occurs at the plate electrodes. Additional information on the precharger is given by Pontius and Sparks (2).

Pilot plant experiments of the two-stage concept, with a nonoptimum collector stage, have been described by Sparks, et al (3). Their results for high resistivity dust are shown in Figure 3. Economic projections based on the pilot plant data show that even with a nonoptimum collector stage the two-stage system should result in a factor 2-1/2 to 3 reduction in ESP capital cost. Optimizing the downstream collector should result in even lower costs and enable us to meet the objective. A 10 MW pilot demonstration of the precharger/collector system is being started. System design has been finalized and startup is expected in early 1980.

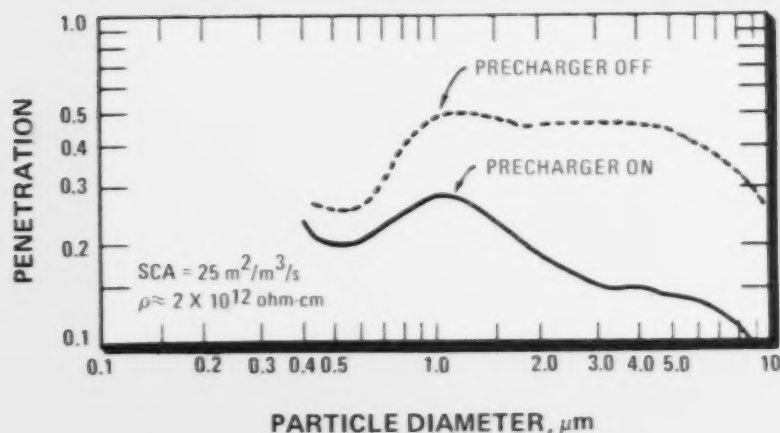


FIGURE 3—Graded penetration curve showing effect of precharger

FABRIC FILTRATION

Although fabric filters have been successfully used to control particulate emissions from small boilers, they have not been used in the U.S. to control particulate emissions from large utility boilers because of the large size of filter systems, the apprehension about fabric durability and mechanical design, and the lack of familiarity with fabric filter technology by utilities. For these reasons most utilities will probably not use fabric filters until they are demonstrated on a large scale—even though fabric filters appear to be economically attractive for low sulfur coal applications.

A contract has been funded with Southwestern Public Service Company (SWPS) to provide the needed full scale demonstration of a fabric filter for control of particulate on a large utility boiler burning western low sulfur coal. A new baghouse began operation in June 1978 on a 356 MW boiler at the Harrington Station of SWPS in Amarillo, Texas. In FY-79, three 1-month detailed emission tests are scheduled to be completed to characterize this fabric filter. The contract will continue until 1984 in order to determine the technical and economic feasibility and the long term reliability of the fabric filter. Preliminary data indicate that particulate emissions are acceptable. However, bag cleaning and system pressure drop problems do exist. Work is underway to resolve these problems. In spite of these problems the costs of fabric filters appear to be reasonable when compared to other conventional technologies for many low sulfur coal applications.

FLUE GAS CONDITIONING

Particle collection by ESP's can be improved by introducing chemicals into the gas stream which alter the electrical properties of the gas, the electrical resistivity of the dust, or some other property of the dust. Sulfur trioxide (SO_3), ammonia, and proprietary chemicals are commercially available conditioning agents. PATB has initiated a program to determine the effectiveness and possible environmental impact of flue gas conditioning. PATB is also sponsoring a demonstration of sodium conditioning. Results, to date, of these two efforts are discussed below.

Field test evaluation of available conditioning agents has shown that SO_3 is an effective flue gas conditioning agent which reduces the electrical resistivity of fly ash (4,5). Field tests of a proprietary agent do not show any improvement in ESP performance (5). The field data also show that SO_3 conditioning can result in significant emissions of SO_3 . This SO_3 can condense in the atmosphere and form a visible plume.

Laboratory studies indicate that triethylamine, which is used in Australia, can react with flue gas components to form significant amounts of nitrosamine.

The demonstration of sodium conditioning follows successful pilot studies. The full scale demonstration is now underway. Preliminary data disclosed mechanical problems associated with distribution of the sodium carbonate/fly ash mixture in the gas stream and on the ESP collector plates. Steps were taken to correct these problems during a recent boiler outage. Data on the system following the boiler's return to service are not available. This demonstration will be completed by late 1973.

FUGITIVE EMISSION CONTROL

Among the standards used by EPA to prevent adverse health and ecological impacts of air pollution is the National Ambient Air Quality Standard (NAAQS). The NAAQS is currently expressed in a number of ways involving the limitation of total suspended particulate (TSP). Unfortunately, the TSP standard is not being met in many air quality control regions. Fugitive dusts account for most of this problem. In 9 out of 10 control regions, fugitive emissions are greater than ducted-point source emissions. In one out of three control regions, fugitive emissions are more than 10 times greater than ducted-point source emissions (6). Within cities the contribution of point sources is expected to be smaller than fugitive emissions. In Philadelphia, more than one-third of the TSP was attributed to reentrained street dust and vehicular traffic; point sources were responsible for less than one-fourth of the TSP.

Because of the importance of fugitive sources in meeting NAAQS, PATB has begun a program of control technology R&D. Described below are two ongoing projects which have been labeled *new concepts*. This term does not imply that such technology has not been previously investigated but rather that the technology has not been fully utilized and will remain new until it is accepted into conventional practice. The two new concepts described here are road carpet and the spray charge and trap (SCAT) system.

ROAD CARPET

The fundamental concept behind use of a fabric roadbed stabilizer, or road carpet, for control of fine particle emissions from unpaved roads is prevention of vortex entrainment by separation of fine roadbed materials from the coarse aggregate where the traffic movement occurs. Large aggregate is held from settling, while newly deposited fines ($< 70 \mu\text{m}$) are filtered by gravitation and hydraulic action down to a zone away from vortex entrainment. Road carpet can be made from spunbonded, thin-film polypropylene on nylon sheet (Celanese), continuous filament polyester fibers needled to form a highly permeable fabric (Monsanto), or other spun or needle-punched synthetic materials. The mechanical interlocking of fibers makes a formed fabric with the durability and toughness required for the proposed use. Designed for road construction use, this fabric is laid over poor loadbearing soils to help support and contain the overburden aggregate. It spreads concentrated stress from heavywheeled traffic over a wider area, siphons away ground water, and contains fine soil particles in the roadbed that can otherwise contaminate ballast or road overburden.

SPRAY CHARGE

Air Pollution Technology, Inc. is studying the second concept, use of the scrubber systems approach in controlling fugitive process emissions (FPE). Figure 4 is a functional diagram for the process anticipated for controlling FPE. The functional phenomena represented in this diagram could occur concurrently or separately in several types of equipment. The control concept is basically a three step process:

- Containment of the FPE with electric or air curtains.
- Treatment with sprays which have electrostatic charge or surface active agents. (When electrostatic charge is used the control concept is the SCAT system.)
- Removal of the droplets in an entrainment separator. PATB has planned an extensive research, test, and evaluation program for both of these concepts.

The research portion will identify parameters affecting the theoretical and economic limitations to utilization of the technology. Preliminary studies of these parameters will provide an understanding for optimization. In the case of road carpet, the vortex entrainment, comminution, and saltation of material on the coarse aggregate must be modeled. Parameters affecting performance may be size and thickness of the aggregate. For the scrubber system using charged water sprays, methods of partial containment of the FPE must be studied as well as fundamentals of droplet/particle interactions.

DIESEL PARTICULATE CONTROL

EPA's Office of Air, Noise, and Radiation, in response to the 1977 Clean Air Act Amendments, is preparing particulate emission standards for light duty diesels in 1981 and heavy duty diesels in 1983. Uncontrolled emissions are approximately as great as 1 gram per mile and the proposed standard for light duty diesel in 1981 is 0.6 grams per mile. A further reduction for light duty diesels in 1983 has been proposed which would set the emission limit at 0.2 grams per mile. In light of the lead time necessary to set standards and to change engine production, these proposed standards require the immediate identification and verification of candidate control technologies. Moreover, biological assays have shown diesel particulate to be mutagenic and hence potentially carcinogenic. Should further testing verify this hazard and U.S. auto manufacturers continue to plan for conversion to diesel cars to meet corporate average fleet fuel economy requirements, even stricter controls may be necessary.

Consequently, PATB has been intensively searching for and reviewing potential control technology approaches. It has been determined that control of diesel particulate is possible with an aftertreatment control device called the Aut-Ainer. According to PATB's Japanese technology transfer contractor, Senichi Masuda, this device is being developed in conjunction with Mitsubishi Motor Company, Inc. Reported collection efficiencies range from 65 percent to 90 percent. The device works by expansion of the exhaust gas through a throttle plate and collection on a metal fiber mat. The filter may be cleaned by flushing to a sump which is periodically purged.

NEW CONCEPTS

Other control approaches are being investigated which utilize technology developed for stationary sources. While conventional configurations of scrubbers, baghouses, and electrostatic precipitators cannot respond to limitations on space and convenient disposal of collected particulate, new concepts involving conventional devices can. The baghouse would become a pleated cartridge filter, the scrubber would become a charged droplet scrubber, and the electrostatic precipitator would become a two-stage precipitator with flushed collection plates. The latter two concepts would remove particulates to a sump which could be periodically purged as with the Japanese control concept. In the case of the pleated filter, the collection media would be a felt ceramic and would be cleaned by combustion or catalytic incineration. Review of these concepts is currently in progress to verify feasibility. Later, bench scale designs will be tested in the laboratory using engine dynamometers to provide the particulate source. Finally, there will be an attempt to demonstrate control with a prototype device on a field tested vehicle.

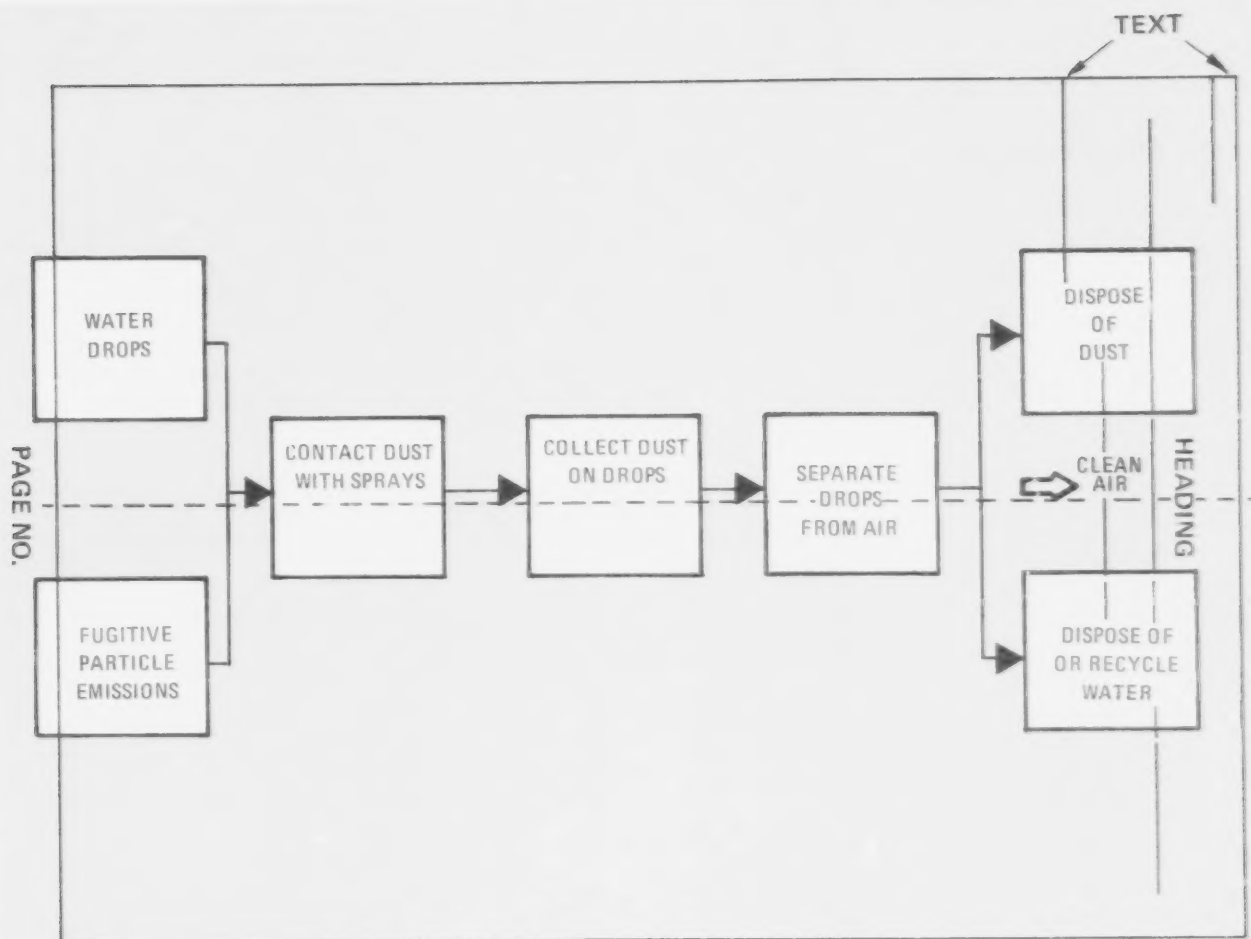


FIGURE 4—Functional diagram for the major process steps involved in controlling fugitive particle emissions with a charged drop system

INHALABLE PARTICULATE AMBIENT STANDARD

In response to the Clean Air Act Amendments of 1977, EPA is considering an ambient air standard for inhalable particles which have been defined as those having aerodynamic diameters less than 15 μm . Consequently, it will be necessary to have emission factors for inhalable particles to provide for implementation of the standard. Particulate emission factors, as compiled in EPA Report AP-42 ("Compilation of Air Pollutant Emission Factors"), estimate the emission of total suspended particulates from uncontrolled sources. This current program is for determining emission factors based on a cut-off size for inhalable particles for both controlled and uncontrolled sources. To achieve the objectives of this program the following steps have already been started:

- Development of sampling techniques to allow assessment of the particulate characteristics based on the inhalable potential.
- Extrapolation of the existing data on particulate characteristics to the inhalable size range where possible.
- Selection of sampling strategies for major sources based on national and regional impact within budgetary constraints.

Since a fine particulate standard may also be desirable in the future as a secondary standard, this program will continue with the development of necessary

measurement techniques and the testing of sources (both point and fugitive) in support of an inhalable particulate primary ambient standard and a fine particulate secondary standard. This data will be used for the development of state implementation plans (SIP's) necessary to the implementation of these future proposed standards.

NOVEL DEVICE PROGRAM

The objective of IERL-RTP's novel device program is to identify and evaluate new technology or new combinations of well studied mechanisms in order to achieve cost effective control of fine particulate. A novel particulate collection device is a device or a dust collection system based on new collection principles or on radical redesign of conventional collectors which are available for testing as pilot or full scale units. In the fall of 1973 the novel device evaluation program was initiated to identify, evaluate, and develop, where necessary, those devices or systems which showed the most promise for high efficiency collection of fine particulate. More than 40 novel particulate collectors have been identified. About half of the devices identified have been of sufficient interest to justify technical evaluations. To date 14 devices have been either field or laboratory tested:

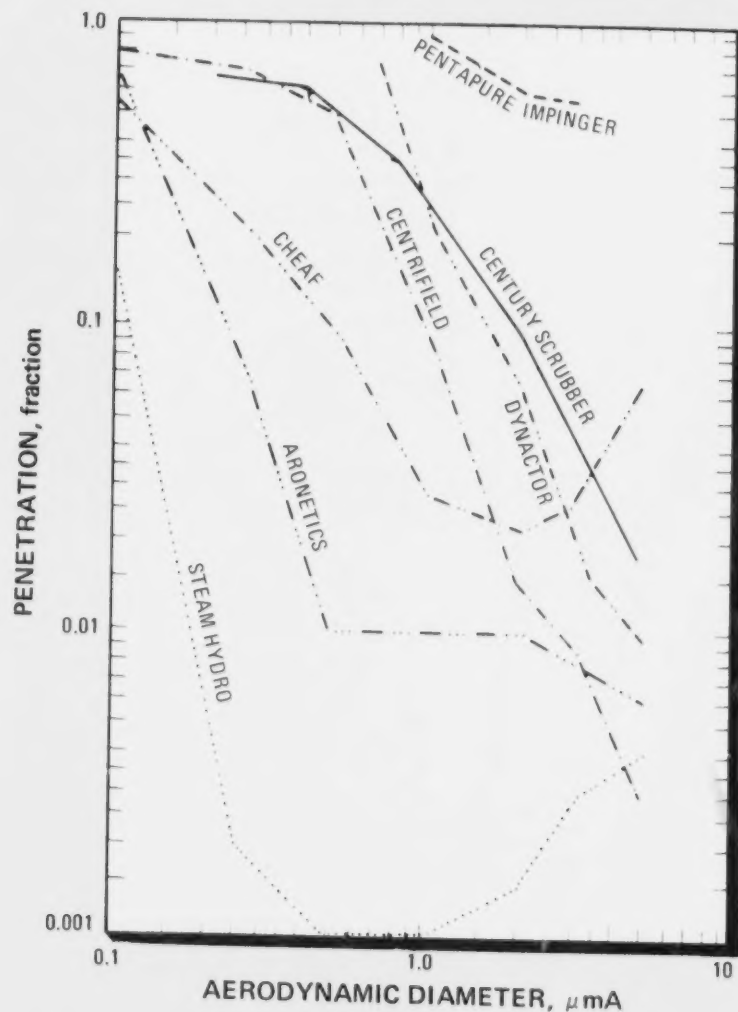


FIGURE 5—Penetration vs. particle size for novel devices tested by EPA

Braxton—Sonic Agglomerator
 Lorie Star Steel—Steam-Hydro Scrubber
 R. P. Industries—Dynactor Scrubber
 Aronetics—Two Phase Wet Scrubber
 Purity Corporation—Pentapure Impinger
 Entoleter—Centrifield Scrubber
 Andersen 2000—CHEAF
 Rexnord—Granular Filter Bed
 Air Pollution Systems—Electrostatic Scrubber (Scrub-E)
 Air Pollution Systems—Electro-Tube
 Century Industrial Products—FRP-100 Low Energy Wet Scrubber
 American Precision Industries—Apitron
 Particulate Control Systems—Electrified Bed
 Ceilcote—Ionizing Wet Scrubber

HIGHEST OVERALL EFFICIENCY

Fractional penetration curves for these devices are shown in Figures 5 to 7. Of all the devices tested, the American Precision Industries' Apitron gave the highest overall mass efficiency and fine particle fractional efficiency—99.9991 percent mass

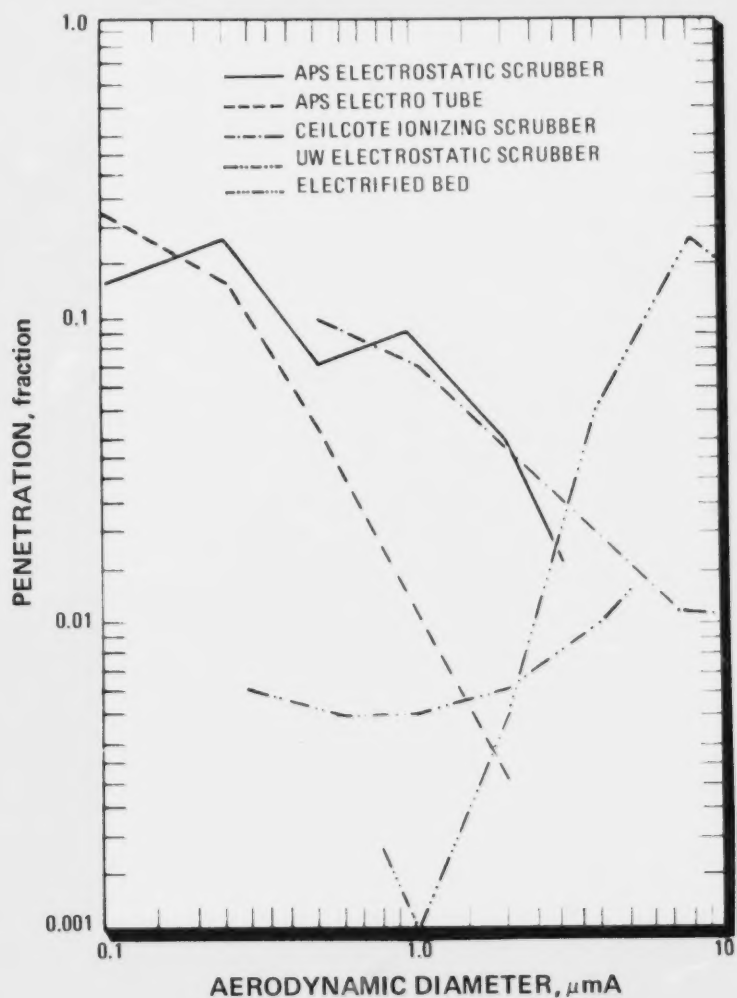


FIGURE 6—Penetration vs. particle size for electrostatically augmented novel devices tested by EPA

efficiency on a redispersed silica dust (8). Collection efficiency on particles between $0.25\text{ }\mu\text{m}$ and $2\text{ }\mu\text{m}$ was greater than 99.9 percent. The Apitron is an electrostatically augmented fabric filter. Without the electrical energy being applied, the collection efficiency was still high—99.997 percent; however, the pressure drop increased by a factor of 3.

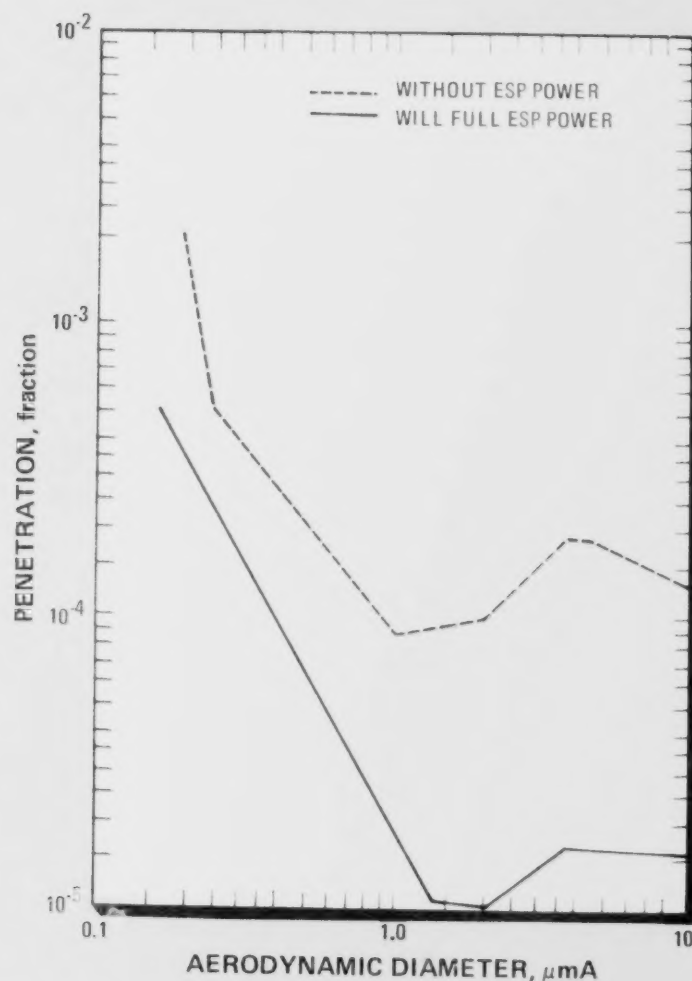


FIGURE 7—Penetration vs. particle size for Apitron unit operating as a conventional fabric filter and with full ESP power

SCRUBBER EFFICIENCY

Of the scrubbers tested, the Lone Star Steel Steam-Hydro Scrubber gave the highest efficiency on fine particulate—99.9 percent efficiency on a fine fume from an open hearth steel furnace. However, intrinsic power consumption is quite high, an order of magnitude greater than an ejector venturi scrubber. If fuel must be purchased to make the steam, the Steam-Hydro system is not an economic alternative to such systems as fabric filtration or electrostatic precipitation. If sufficient waste heat is available, the Steam-Hydro system becomes economically feasible (9). The Aronetics Scrubber is similar to the Steam-Hydro Scrubber but instead of steam it discharges high-pressure/high temperature (200°C) water through a nozzle to provide small high-velocity water droplets. The Aronetics unit, tested

on a ferroalloy plant, was not quite as efficient as the Steam-Hydro unit (10). The Air Pollution System (APS) electrostatic scrubber was equal in fractional collection efficiency to a venturi scrubber using 2-1/2 times as much energy (11). This system will be discussed in more detail later. The Ceilcote Ionizing Wet Scrubber was similar in performance to the APS Electrostatic Scrubber. The APS Electro-Tube, which is similar to a wet-wall ESP, gave some very high collection efficiencies on fine particles— as high as 98.9 percent on 0.5 μ m particles. This performance is similar to that which can be achieved in small wet ESP's with the same ratio of plate area to volumetric flow rate as the Electro-Tube unit tested (8).

NOVEL CONCEPTS PROGRAM

The major difference between the Novel Device and Novel Concepts program areas is that the device program deals with existing equipment which is either offered commercially or available for pilot scale testing and the concepts program deals with the development of equipment from untried ideas or from the results of proven research which shows that the development of an idea is feasible.

Most work to date has been directed toward combining electrostatic removal mechanisms with scrubbing or filtration mechanisms. The first area to be developed was charged droplet scrubbing, with a feasibility study at M.I.T. (12) and a pilot demonstration at TRW on a Kaiser coke oven (13). Electrostatics and filtration have been studied at both Battelle Northwest (14) and Carnegie-Mellon (15,16)—the former with bed filters, the latter with baghouses. At least two new concepts, a ceramic membrane filter and a magnetic fiber bed, are oriented toward cleanup of high temperature gases (1900-2000°F/500-1100°C). Other new concepts which have been studied are foam scrubbing and pleated cartridge filters of a novel material.

Of the advanced electrostatic collection concepts studied, those employing water droplets or filters have demonstrated enhanced performance and should be considered for future applications. Electrostatic collection with water drops shows high removal efficiencies for 0.5 μ m particles which are difficult to capture. Electrostatic collection with filters shows the potential for operation at either lower pressure drops or higher filtration rates. Some electrostatic collection concepts are given in Table 1. In general, the entries in Table 1 reflect the three major categories of collection mechanisms: electric field effects, scrubbing, and filtration. For the last two, combining electrostatic effects and conventional mechanisms enhances performance over conventional devices of the same type. The possibility of enhanced performance stimulated EPA's involvement in developing advanced electrostatic collection concepts. Two of the demonstrations discussed in the next section are based on electrostatic collection concepts.

TABLE 1
Electrostatic collection concepts

Concept	Collection by means of	EPA Activity
Electrostatic Scrubbing	Electric field and water droplets	Contract 68-02-0250, MIT Contract 68-02-1345, TRW
Charged Droplet Scrubbing	Water droplets	Grant 803278, University of Washington Grant 804393, University of Washington Contract 68-02-2666, Air Pollution System
Electrostatic Fiber Beds	Filter fibers	Grant 801581, Battelle Northwest
Electrostatic Effects in Fabric Filters	Filter fabric	Grant 803020, Carnegie-Mellon University

Three particulate collection systems, identified and/or developed under the Novel Device and Novel Concepts Programs, are being demonstrated by EPA at pilot scale. These systems are the University of Washington (UW) Electrostatic Scrubber, the Air Pollution Systems (APS) Electrostatic Scrubber (Scrub-E), and the High Gradient Magnetic Separator (HGMS).

SUMMARY

In summary we will briefly discuss where each of the major research areas stands and also describe some of the unresolved problems in each area.

The Low Sulfur Coal Program is a mature program and has several projects in the demonstration phase. We fully expect to meet the program objectives of:

- Reducing capital cost of ESP by a factor of 3 to 5.
- Demonstrating that fabric filters are a cost effective method of particulate control.
- Assessing the environmental impact of flue gas conditioning agents.

Some major unresolved problems in the low sulfur program area are:

- What is the least costly method of controlling particulate and sulfur oxide emissions?
- What technologies are most applicable for meeting prevention of significant deterioration requirements?
- What is needed to meet opacity standards?

The Fugitive Emission Program is relatively new. The two fugitive emission control concepts discussed in this paper promise significant improvements in controlling fugitive emissions. Additional research and development is needed to develop more technology for fugitive emission control.

The Novel Device and Novel Concepts Programs are mature programs. Several commercial devices have been evaluated. Three concepts have been developed to the pilot or full scale demonstration phase.

NEW PROGRAMS

The Inhalable Particulate Program is brand new. We expect to start field work to acquire data for emission factors this month. As the program develops, we expect to identify areas where particulate control technology is needed and will plan the research needed to develop the required control technology. The diesel emission program is also new.

We plan to begin the testing of devices for tailpipe exhaust gas cleanup in November of this year.

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DISPOSAL OF WASTES FROM COAL-FIRED POWER PLANTS

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COAL ASH PRODUCTION

Modern fossil-fueled, steam-electric generating plants present the full spectrum of potential environmental problems—pollution of air and water and generation of large quantities of solid waste. Essentially all of the solid wastes, except for bottom ash, are generated by air pollution control devices—mechanical collectors (e.g., cyclones), electrostatic precipitators, baghouses, and scrubbers—to control emissions of fly ash and sulfur dioxide (SO_2). Although there are other wastes, such as those from water treatment systems, the quantities of these are small compared with the large amounts of ash and SO_2 scrubber waste produced.

COAL ASH UTILIZATION

Coal ash production by electric utilities is expected to reach 65 million metric tons per year, including over 45 million metric tons per year of fly ash, by 1980 (1). U.S. electric utility commitments to SO_2 scrubbers, or flue gas desulfurization (FGD) systems, currently total about 62,500 Mw of electrical generating capacity (2). Approximately 10 million to 15 million metric tons per year (dry) of FGD wastes, exclusive of fly ash, are expected to be produced by the mid-1980's, when all these plants are onstream.

Extensive utilization of coal ash is both technically and economically feasible. For example, fly ash can be admixed with portland cement clinker in an ash:clinker ratio as high as 1:5. With portland cement production in the U.S. currently around 80 million metric tons per year, this means that approximately one-third of the 1980 fly ash production could be used for this single application. However, current utilization of fly ash for all applications is just 13 percent of production, according to the National Ash Association (3).

In 1975 Japan produced more than a million metric tons of gypsum by FGD processes, primarily for use in wall board and portland cement (4). TVA recently

completed a study for EPA which indicates that approximately two-thirds of the gypsum requirements for the portland cement industry in the U.S. could be supplied by FGD systems in a competitive market (5). However, this use would consume only about 20 percent of the FGD waste expected to be produced in the mid-1980's. On the other hand, a shift to grass-roots wallboard plants near power plants, instead of near natural gypsum delivery points, could increase this percentage substantially. The wallboard industry currently consumes about 11 million metric tons of gypsum annually, almost four times the annual consumption of the portland cement industry (5).

In any event, because of the current lack of market demand for coal ash and FGD wastes, most electric utilities find disposal of these wastes the most attractive choice. However, once the decision is made in favor of disposal, the environmental and economic effects of the various disposal options have to be addressed.

COAL ASH DISPOSAL

Disposal of coal ash, either in ponds or landfills, has been practiced for many years. Ash ponds at power plants overflow to watercourses in numerous locations. Until recently, this was not of major environmental concern, very likely because the major chemical constituents of fly ash (i.e., those comprising the greatest percentage by weight) have very low solubility. However, both existing and pending regulations on plant discharges and disposal of wastes on the land have caused a trend toward (a) dry ash handling and disposal in a landfill or (b) codisposal of ash with FGD waste, either in a zero-discharge pond with recycling of water to the plant or as part of an FGD waste treatment process.

FGD WASTE DISPOSAL

Initially, FGD waste was disposed of in ponds, usually along with fly ash from the plant. However, FGD systems have been in the limelight since early in the period of U.S. environmental awareness, and very early in their commercial history there was concern about disposal of wastes from these systems because (a) the large amount of occluded water in the wastes or sludges made them physically unstable; (b) the variable physical and chemical properties of the wastes made them an "unknown" material; and (c) the soluble and slightly soluble chemical constituents in the wastes made them potential sources of water pollution. Consequently, considerable research and development was undertaken by governmental and private organizations. These efforts have resulted in a better understanding of the nature of FGD wastes and a trend toward more environmentally acceptable and cost-effective methods of disposal, either in ponds lined with clay or other low permeability material to reduce their potential for water pollution or in a landfill usually after chemical treatment of the waste to improve its physical stability and reduce its permeability.

Other methods of coal ash and FGD waste disposal are currently being considered, including the return of these wastes for use in coal mine reclamation. At least two plants, in North Dakota and Texas, are already disposing of the wastes in this manner. Disposal in the ocean, possibly by construction of an artificial reef of treated "blocks" of FGD waste and fly ash, is also being studied; the environmental acceptability of this method has not yet been demonstrated.

PRESENT REGULATORY FRAMEWORK

Table 1 shows Federal legislation that applies to the handling and disposal of coal ash and FGD waste in ponds, landfills, coal mines, and the ocean. The two legislative Acts that have the greatest impact on disposal of these wastes are the Federal Water Pollution Control Act (FWPCA) and the Resource Conservation and Recovery Act (RCRA).

The FWPCA of 1972 established a system whereby all discharges to navigable waters require a permit, issued by EPA or a state delegated the authority by EPA. This Act also required industries to use beginning July 1, 1977, the "best practicable" control technology currently available (BPCTCA) to control pollutant discharges, and requires application of "best available" technology economically achievable (BATEA) by July 1, 1983. EPA established national effluent guidelines, based on BPCTCA and BATEA, for existing power plants, as well as New Source Performance Standards (NSPS) for plants for which construction was initiated after the regulations were proposed. Table 2 summarizes effluent guidelines and standards for steam-electric power plant ash ponds.

TABLE 1

Federal regulatory framework for disposal of coal ash and FGD waste

Possible Environmental Impact	Legislation	Administrator
Surface Water Contamination	• Federal Water Pollution Control Act of 1972 and Amendments of 1977	• Environmental Protection Agency
Groundwater Contamination	• Resource Conservation and Recovery Act of 1976 • Safe Drinking Water Act of 1974	• Environmental Protection Agency • Environmental Protection Agency
Waste Stability/Consolidation	• Dam Safety Act of 1972 • Surface Mining Control and Reclamation Act of 1977 • Occupational Safety and Health Act of 1970 • Federal Coal Mine Health and Safety Act of 1969	• Army Corps of Engineers • Office of Surface Mining Reclamation and Enforcement • Occupational Safety and Health Administration • Mining Enforcement Safety Administration
Fugitive Air Emissions	• Clean Air Act • Hazardous Materials Transportation Act of 1975 • Federal Coal Mine Health and Safety Act of 1969 • Occupational Safety and Health Act of 1970	• Environmental Protection Agency • Department of Transportation • Mining Enforcement Safety Administration • Occupational Safety and Health Administration
Contamination of Marine Environment	• Marine Protection Research and Sanctuaries Act of 1972	• Environmental Protection Agency

TABLE 2

Effluent guidelines and standards for power plant ash ponds

Discharge Stream	Controlled Parameter	BPCTCA*		BATEA*		NSPS*	
All Plant Discharges	pH	6.0-9.0		6.0-9.0		6.0-9.0	
	polychlorinated biphenyls (PCBs)	zero		zero		zero	
		30-day average	daily maximum	30-day average	daily maximum	30-day average	daily maximum
Bottom Ash Transport Water	total suspended solids (TSS)	30	100	30±12.5†	100±12.5	30±20	100±20
	oil and grease	15	20	15±12.5	20±12.5	15±20	20±20
Fly Ash Transport Water	TSS	30	100	30	100	zero	zero
	oil and grease	15	20	15	20	zero	zero

*All quantities except pH are in units of mg/l.

†±12.5 or ±20 indicates the required degree of recycle (or "number of cycles") of water;
 ±12.5 means 8% blowdown allowed, while ±20 means 5% blowdown allowed.

CLEAN WATER ACT

The FWPCA Amendments of 1977, or the Clean Water Act (CWA), require review of the BATEA and the NSPS, particularly regarding the discharge of "priority pollutants," 129 potentially hazardous pollutants, including heavy metals. The date of BATEA compliance is a function of the type of pollutant and the level of treatment possible. Changes to the regulations on ash pond discharges currently under consideration include limitations on certain trace metals, zero discharge for bottom ash (BATEA and NSPS), and possibly zero discharge for fly ash (BATEA). The modified regulations are expected to be proposed later this year.

No guidelines or standards have been promulgated specifically for FGD systems, although the limitations for low volume waste streams are currently being applied. In general, it is assumed that there will be no direct discharge from these systems. However, because of operational problems which require extra water, some of the commercial FGD systems have entailed a discharge. Nevertheless, these systems were designed to operate "closed-loop," that is, the only discharge of water would be that associated with the FGD waste. In the more recent systems to come on line, this design feature is operational.

GROUNDWATER CONTAMINATION

With no direct discharge from FGD systems, the major environmental concern associated with FGD waste disposal is the potential contamination of groundwater. This can also be said of an ash pond with no discharge, or of disposal of ash in a landfill. The major Federal legislation which addresses these potential problems is the RCRA. Before enactment of the RCRA, there was no comprehensive Federal authority to regulate disposal of wastes. This Act is designed to eliminate improper disposal of wastes through Federal regulation of hazardous-waste* disposal and state regulation (with Federal assistance) of nonhazardous solid waste disposal. The Act defines a hazardous waste as a waste which poses a "substantial present or potential hazard to human health or the environment" if improperly managed.

Regulations for the identification, handling, and disposal of hazardous wastes were proposed in December 1978(6). The criteria for identifying hazardous wastes include characteristics such as ignitability, corrosivity, reactivity (e.g., strong oxidizing agents), and toxicity. The protocol for handling toxicity includes subjecting the waste to an extraction procedure (EP), followed by chemical analysis of the extract for eight trace metals and six pesticides. If the concentration of any of the metals or pesticides exceeds 10 times the EPA National Interim Primary Drinking Water Standards, the waste is considered to be hazardous.

SPECIAL WASTES

The proposed regulations also included a list of wastes that EPA considers to be hazardous. Neither coal ash nor FGD waste was on the list. However, EPA recognized that some percentage of the coal ash and FGD waste might fail the toxicity criteria because of excessive concentrations of one or more of the eight trace metals. (Concentrations of these metals are primarily a function of the coal composition, although they also vary with the type of FGD system and with operating parameters.) Nevertheless, EPA also recognized that "such waste occurs in very large volumes, that the potential hazards posed by the waste are relatively low, and that the waste is not amenable to control techniques..." required under the Standards Applicable to Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities (6). For this reason, hazardous coal ash and FGD wastes are considered "special wastes" and will very likely be subject to standards less stringent than the general hazardous-waste disposal standards.

In the December 1978 announcement EPA indicated that proposed rules regarding the treatment, storage, and disposal of special wastes would be published at a later date. In the interim, however, many of the general facility standards (e.g., waste analysis, security, recordkeeping, groundwater monitoring) will apply to these wastes.

*EPA may authorize state agencies to implement their own programs if the programs are deemed equivalent to EPA regulations for hazardous-waste disposal.

Coal ashes and FGD wastes that meet the toxicity criteria are not considered hazardous (or special) wastes and therefore will be regulated under the nonhazardous sections of RCRA. EPA is required by RCRA to issue regulations for nonhazardous waste disposal, but the authority to implement and enforce these regulations rests with the states. Each state may receive Federal assistance in this effort, if it adopts and enforces the EPA regulations for disposal of nonhazardous waste.

R&D WASTE DISPOSAL PROGRAM

In 1972, EPA initiated a major program of research and development (R&D) in the area of FGD waste disposal. The primary objectives of the program were better quantification of potential environmental problems associated with FGD waste disposal and better assessment of FGD waste disposal technologies. Coal ash disposal alone was not investigated under this initial program. However, since in most instances FGD waste either contains fly ash (collected in the scrubber) or is mixed with ash prior to disposal, any thorough study of FGD waste, such as was conducted under this program, includes a study of fly ash. Because of this rather inseparable relationship between FGD waste and fly ash, the term "flue gas cleaning (FGC) wastes" was coined to cover both wastes.

In late 1974, plans were formulated to greatly expand EPA's FGC waste-related R&D efforts as part of the Interagency Energy/Environment R&D Program. These efforts included continuing to improve quantification of potential environmental problems (of the 1972 program). They were also aimed at reducing costs, investigating a broader range of alternative waste disposal options, and examining possible uses of the wastes. The Interagency Energy/Environment R&D Program dealing with disposal of power plant wastes is part of a larger program that involves control of waste and water pollution. The Waste and Water Program, as the larger program is known, is divided into four major areas:

- FGC waste disposal
- FGC waste utilization
- Effluent treatment
- Water recycle/reuse

Each of these program areas comprises a number of projects. These are listed in Table 3. The FGC waste disposal area of the Waste and Water Program consists of 20 projects, 7 of which were recently completed. In addition, three of the five water recycle/reuse projects are directly related to FGC waste disposal. The discussion which immediately follows describes some of the significant accomplishments of these projects.

TABLE 3
Projects in the waste and water program

Project Title	Contractor/Agency
FGC WASTE DISPOSAL	
Assessment of Technology for Control of Waste and Water Pollution	Arthur D. Little, Inc.
* FGC Waste Characterization, Disposal Evaluation, and Transfer of FGC Waste Disposal Technology	The Aerospace Corporation
† Characterization and Monitoring of Full-Scale Utility Waste Disposal Sites	Contractor Not Yet Selected

*Project completed

†Direct support of regulation development

Table 3 (Continued)

Project Title	Contractor/Agency
* † Solid Waste Impact of Controlling SO ₂ Emissions from Coal-Fired Steam Generators	The Aerospace Corporation
Laboratory and Field Evaluation of 1st and 2nd Generation FGC Waste Treatment Processes	U.S. Army Corps of Engineers (Waterways Experiment Station)
Ash Characterization and Disposal	Tennessee Valley Authority
* Studies of Attenuation of FGC Waste Leachate by Soils	U.S. Army Test and Evaluation Command (Dugway Proving Ground)
* Establishment of Data Base for FGC Waste Disposal Standards Development	Stearns, Conrad and Schmidt Consulting Engineers, Inc. (SCS Engineers)
Development of Toxics Speciation Model and Economic Development Document for FGC Waste Disposal	SCS Engineers
Shawnee FGC Waste Disposal Field Evaluation	Tennessee Valley Authority The Aerospace Corporation
* Louisville Gas and Electric Evaluation of FGC Waste Disposal Options	Louisville Gas & Electric Co. (Subcontractor: Combustion Engineering, Inc.)
FGC Waste Leachate/Liner Compatibility Studies	U.S. Army Corps of Engineers (Waterways Experiment Station)
Lime/Limestone Wet Scrubbing Waste Characterization and Disposal Site Revegetation Studies	Tennessee Valley Authority
* Development of EPA Pilot Plant Test Plan To Relate FGC Waste Properties to Scrubber Operating Variables	Radian Corporation
* Dewatering Principles and Equipment Design Studies	Auburn University
Pilot Demonstration of Advanced Gravity Settler	Auburn University
Conceptual Design/Cost Study of Alternative Methods for Lime/Limestone Scrubbing Waste Disposal	Tennessee Valley Authority
Evaluation of FGC Waste Disposal in Mines and the Ocean	Arthur D. Little, Inc.
† Evaluation of Power Plant Wastes for Toxicity as Defined by RCRA	Radian Corporation Department of Energy (Oak Ridge National Laboratory)
† Study of Nonhazardous Wastes from Coal-Fired Utilities	Radian Corporation
FGC WASTE UTILIZATION	
* Gypsum Byproduct Marketing Studies	Tennessee Valley Authority
Pilot Studies of a Process for Recovery of Sulfur and Calcium Carbonate from FGC Waste	Pullman-Kellogg

* Project completed

† Direct support of regulation development

Table 3 (Concluded)

Project Title	Contractor/Agency
Fertilizer Production Using Lime/Limestone Scrubbing Wastes	Tennessee Valley Authority
* Use of FGC Waste in a Process for Alumina Extraction from Low-Grade Ores	TRW, Inc.
EFFLUENT TREATMENT	
Characterization of Effluents from Coal-Fired Power Plants	Tennessee Valley Authority
Treatment of Power Plant Wastes with Membrane Technology	Tennessee Valley Authority
* Alternatives to Chlorination for Control of Condenser Tube Biofouling	Monsanto Research Corporation
† Assessment of the Effects of Chlorinated Seawater from Power Plants on Aquatic Organisms	TRW, Inc.
*† Evaluation of Dechlorination for the Removal of Total Residual Oxidants in Salt Water Cooling Systems	TRW, Inc.
* Bromine Chloride—An Alternative to Chlorine for Fouling Control in Condenser Cooling Systems	Martin Marietta Corporation
† Evaluation of Lime Precipitation for Treatment of Boiler Tube Cleaning Waste	Hittman Associates, Inc.
*† Assessment of Technology for Control of Toxic Effluents from the Electric Utility Industry	Radian Corporation
*† Field Testing/Laboratory Studies for Development of Effluent Standards for Electric Utility Industry	Radian Corporation
Effects of Pathogenic and Toxic Material Transported via Cooling Device Drift	H ₂ M, Inc.
Assessment of Measurement Techniques for Hazardous Pollution from Thermal Cooling Systems	Lockheed Electronics Co. Northrop Corporation
WATER RECYCLE/REUSE	
* Assess Power Plant Water Recycle/Reuse	Radian Corporation
† Pilot Demonstration of Closed-Cycle Ash Sluicing	Radian Corporation
*† Water Pollution Impact of Controlling SO ₂ Emissions from Coal-Fired Steam Generations	Radian Corporation
Power Plant Cooling Tower Blowdown Recycle by Vertical Tube Evaporator With Interface Enhancement	University of California - Berkeley
* Treatment of Flue Gas Scrubber Waste Streams With Vapor Compression Cycle Evaporation	Resources Conservation Company

*Project completed

†Direct support of regulation development

FGC WASTE CHARACTERISTICS

The chemical characteristics of FGC scrubber waste have, to a large degree, been quantified. FGC waste liquors have been shown to exceed drinking water standards for total dissolved solids (TDS), with high concentrations of calcium, sulfate, and chloride, and, in some cases, fluoride, magnesium, and sodium. In addition, concentrations of several trace metals have been noted in excess of drinking water standards. The chemical composition of FGC waste solids consists of calcium sulfite hemihydrate, calcium sulfate dihydrate (gypsum) and/or hemihydrate, and calcium carbonate, plus any fly ash collected in the scrubber. The percentage of each solid constituent is primarily a function of the alkaline additive (e.g., lime, limestone), the sulfur in the coal, and the manner in which the scrubber system is operated (e.g., whether forced oxidation is applied, whether fly ash is collected separately). Although fly ash has been shown to be a major contributor of trace elements to the waste solids and liquor, separate collection of fly ash does not necessarily mean that concentrations of all these elements in the waste liquor will be insignificant (7).

A compilation of existing data on coal ash, generated by TVA and others, was issued in early 1977 (8). This report showed that a number of potentially hazardous trace constituents tend to be concentrated in fly ash (as opposed to bottom ash). Further efforts are currently under way to better define this preferential "partitioning" of chemical constituents between fly ash and bottom ash, as well as the concentration of specific constituents as a function of particle size. This latter information would be especially significant in understanding the effect of the presence or absence of fly ash on FGD waste liquor composition.

CHEMICAL COMPOSITION

The physical properties of FGC waste vary considerably from system to system. Chemical composition is related to, but does not adequately define, the size and type of the solid crystals. For example, in comparing the lime and limestone scrubber solids from the EPA/TVA Shawnee test facility, the limestone scrubber solids were found to be primarily individual platelets or "rosette" aggregates, while the lime scrubber solids were primarily spherical aggregates with somewhat better settling and dewatering properties. However, the chemical compositions of the solids from both scrubbers were quite similar.

Regardless of the chemical composition, when FGC wastes are not adequately dewatered (or are allowed to "rewet" after dewatering), they tend to be physically unstable, or fluid, with little or no compressive strength. This physical instability of FGC wastes and the pollution potential of chemicals dissolved in the occluded water are the two major environmental concerns associated with disposal of these wastes.

FGC WASTE DISPOSAL TECHNOLOGY

Several approaches for improving the physical stability of FGC wastes have been, and continue to be, studied as part of a disposal method. A basic feature of all approaches is the removal of sufficient water from the waste, either physically or chemically (or by a combination of the two), to achieve physical stability. Occluded water is more easily removed physically if the solid particles are large enough to settle rapidly or if they provide a sufficiently porous structure for mechanical water removal (e.g., filtration). Difficulty in physical dewatering of FGC wastes is normally attributed to the small platelet crystalline structure of calcium sulfite. However, some forms of calcium sulfite crystals are more easily dewatered than others, suggesting the possibility of avoiding the less desirable forms by proper scrubber operation.

At the present time, the relationship between the scrubber operating parameters and the characteristics of the calcium sulfite crystals has not been adequately defined although certain qualitative observations, such as the comparison between lime and limestone scrubbers mentioned above, have already been made. For example, in limestone scrubbing systems there appears to be an inverse relationship between sulfite crystal size and limestone additive stoichiometry (9). In addition, in tests with lime at Louisville Gas and Electric's Paddy's Run station, calcium sulfite crystals formed in a large (high retention time) tank were mostly individual platelets, whereas crystals formed in a small (low retention time) tank were primarily aggregates of platelets (10).

To better define the relationship between scrubber operation and calcium sulfite crystals, crystal nucleation and growth were studied. This study resulted in a computer model and a test plan for both completion of the model and definition of the scrubber/crystal relationship (11). The tests will be conducted at the EPA/IERL-RTP

pilot plant facilities later this year. We hope this testing will result in the development of procedures for obtaining consistent, easily dewatered calcium sulfite solids.

DEWATERING EQUIPMENT

A complementary approach to improving the quality of calcium sulfite solids would be to improve the performance of dewatering equipment. Laboratory pilot-scale testing using calcium sulfite waste from Louisville Gas and Electric has shown current commercial gravity settling devices (clarifiers, thickeners) to be far from optimum. A design approach has been developed whereby the clarification and thickening functions of the gravity settler have been separated into two pieces of equipment, each of which can be optimized for its function. The result is improved dewatering (thicker underflow) and satisfactory clarification (without using flocculants), with substantially smaller and less expensive equipment. Current plans are to demonstrate this design approach on a large pilot scale at TVA's Shawnee steam plant near Paducah, Kentucky. Testing should be underway by September or October 1979. A paper describing the laboratory pilot results was presented in June 1978 (12).

One way to avoid the dewatering problems associated with calcium sulfite crystals in FGC waste is to use oxidation techniques to produce calcium sulfate or gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Gypsum crystals are typically much larger and thicker than sulfite crystals; therefore, they settle more quickly and trap less water upon settling. Oxidation of the calcium sulfite outside of the scrubber system, although feasible, is more expensive than oxidation within the scrubber loop, which is simpler and therefore less expensive. The latter approach has been successfully tested at the laboratory and large field pilot levels (13), (14), and commercial systems are now being offered by experienced suppliers. Forced oxidation of calcium sulfite to gypsum will be tested on a commercial scale system at TVA's Widow's Creek steam plant.

FIXATION PROCESSES

Many utilities are currently choosing chemical treatment (sometimes called fixation) processes to physically stabilize their FGC waste. Field testing these processes under the EPA Waste and Water Program has shown that the treated waste exhibits significant structural improvement, at least a 50 percent reduction in major solubles (e.g., chloride) in the leachate, and an order of magnitude or more reduction in permeability (15). Another advantage of chemical treatment is that coal ash can be codisposed of, along with the FGC waste.

Other stabilization/disposal techniques are being evaluated, such as underdrainage and compaction of untreated FGC wastes and the production/disposal of gypsum. A paper describing recent results of this evaluation was presented in June 1978 (16). In areas with appreciable rainfall, the underdrainage approach appears to require division of the disposal area into several sections; that is, over the life of the plant, disposal would be accomplished one section at a time. For gypsum disposal in a pile, considerable maintenance may be required because of surface cracking from freeze/thaw cycles and/or erosion from rainfall (16).

FGC WASTE DISPOSAL COSTS

Along with the technical/environmental evaluation of alternative FGC waste disposal techniques, the costs of each technique have also been determined. Preliminary estimates, in 1977 dollars, for a typical high-sulfur coal-fired plant have been recently reported. These show ponding costs of about \$5 to \$8 per metric ton (dry solids, including fly ash) and chemical treatment/landfill costs of about \$10 per metric ton (same basis as ponding) (17). More detailed cost estimates (in 1980 dollars), show ponding costs of about \$9 per metric ton and chemical treatment/landfill costs of about \$14 per metric ton (18). (It should be noted that the \$14 figure includes all dewatering equipment; the earlier \$10 figure assumed the clarifier/thickener to be part of the scrubber system. Clarifiers were excluded in both ponding cost estimates.) Detailed cost estimates (also in 1980 dollars) for direct landfill of FGC gypsum waste (including fly ash) indicate a cost of about \$11 per metric ton (19). These estimates assumed that FGC gypsum wastes could be disposed of using normal landfill techniques, an assumption that has not been commercially demonstrated. Estimates of the costs of coal ash disposal by ponding and landfilling are currently under way.

A cost of \$14 per metric ton for FGC waste disposal converts to about 1.5 mills/kWhr revenue requirement, which compares to a total FGC system revenue requirement of about 5 mills/kWhr. Thus it is clear that waste disposal costs are a

major part of FGC system costs and, further, that any significant savings in waste disposal costs will substantially reduce total system costs.

A number of the efforts described above, e.g., improving performance of dewatering equipment, are aimed at reducing disposal costs. Other efforts will be studied in the near future, e.g., using only the minimum quantity of fly ash required to chemically treat the FGC waste and marketing the excess.

Another approach to reduce costs is to use disposal methods which avoid the need for a specially prepared disposal site (e.g., a pond). Two methods currently under study are disposal in coal mines and at sea.

COAL-MINE DISPOSAL

Coal-mine disposal of FGC waste has greatly interested engineers in the FGD industry for many years because of established means of transportation between the coal mine and the power plant and because of the need for material to fill the void left by coal mining. Also, many plants do not have sufficient land area for on-site disposal. The same reasoning can, of course, be applied to coal ash alone. Preliminary technical/economic assessments conducted under the EPA Waste and Water Program indicated that active area surface mines are the most promising candidates for this disposal approach (20).

FGC waste from the Milton R. Young Station of Minnkota Power Cooperative near Center, North Dakota, is currently being disposed of in an area surface mine near the plant. Ash from this plant has been disposed of in the mine for some time. Under EPA sponsorship, a 2-year assessment of the environmental effects of this operation is being conducted by the University of North Dakota and the North Dakota State Geological Survey. The assessment is expected to be completed in late 1979. Successful demonstration of this disposal approach could make conversion to coal quite feasible even in areas where land for disposal is limited.

Preliminary costs of mine disposal were also determined. A wide range, from about \$4 to about \$10 (in 1977 \$) per metric ton of dry solids, depending on treatment, if used, and transportation costs, was reported (20). More detailed costs of this disposal option are being prepared.

At-sea disposal of FGC waste is also being assessed, because many plants in the Northeast may have difficulty switching to coal for lack of disposal sites. Many of these plants, however, do have access to the ocean. It was also recognized that the major soluble chemical constituents in FGC waste are found in relatively high concentrations in seawater. This assessment has identified several potential environmental problems, the greatest of which is sulfite toxicity. It appears that these problems could be alleviated either by chemical treatment to a brick-like form or by oxidation to gypsum. Preliminary costs of this approach were estimated to be about \$4 to about \$8 [(treated) (in 1977 \$)] per metric ton of dry solids for disposal on the Continental Shelf; deep ocean disposal would be expected to add another \$3 to \$4 per metric ton to these costs (20). More detailed costs for this disposal method are being prepared. Pilot disposal simulation studies are under way to define the environmental effects of both untreated and treated FGC sludge disposal at sea.

ARTIFICIAL REEF CONSTRUCTION

In addition, a large-scale pilot effort is under way to demonstrate the feasibility of artificial reef construction using treated blocks of FGC waste. This project is being conducted under the joint sponsorship of EPA, the Electric Power Research Institute (EPRI), the Department of Energy (DOE), the Power Authority of the State of New York, and the New York State Energy Research and Development Authority (NYSERDA). Blocks will be fabricated in the spring of 1980, then placed in an approved artificial reef site in the Atlantic Ocean near Long Island. The reef will be monitored for environmental effects and structural integrity for about 3 years.

WATER RECYCLE/REUSE

With the exception of dry ash handling and disposal, FGC waste operations at power plants involve the use of vast quantities of water. All operational FGD systems employ recirculation within the scrubber loop as well as recycling and reuse of clarified liquor from the waste dewatering system. On the other hand, ash sluice systems are typically once-through operations; the excess water is either returned to the source

(e.g., a river) or is evaporated. Because of the scarcity of water in some areas of the country, environmental limitations on chemical discharges, and the realization that better water management—including recycle/reuse—can in some cases reduce costs, water recycle/reuse has become a topic of major interest.

Under the Waste and Water Program, water recycle/reuse efforts which relate directly to FGC waste disposal have resulted in the following accomplishments:

- A general methodology was developed for use in a water management plan/design for the major water use systems in a coal-fired power plant, i.e., the cooling system, the ash sluicing system, and the FGD system (21). Through the use of this methodology, all three of these systems can be interconnected, with blowdown from one system used as feed for another. For example, cooling tower blowdown might be used for ash sluicing, or ash sluice recycle water might be used for scrubber makeup.
- A vapor-compression evaporative system (used commercially to treat cooling tower blowdown) was tested in the treatment of FGC scrubber liquor which contained very high concentrations of dissolved salts and high total dissolved solids (TDS) (22). The pilot demonstration test was successful. This type of system might be necessary in cases where very little freshwater makeup was required in the FGD system (i.e., for a very tight closed-loop operation) or if the makeup water quality was unacceptable.

A project was recently initiated to demonstrate, on a pilot scale, closed-loop (zero-discharge) ash sluicing. The project is cosponsored by EPA's IERL-RTP and Effluent Guidelines Division in support of development of effluent guidelines under the Clean Water Act. The principles involved in the general recycle/reuse methodology already discussed will be used to design the pilot ash sluicing system, which will be field tested at three coal-fired power plants. Both bottom ash and fly ash will be tested at each plant. Side-stream treatment of the sluice water will be applied as needed to prevent corrosion from and/or precipitation of dissolved salts, which will be increasingly concentrated as the water is recycled. Successful demonstration of this technology would provide an alternative to dry ash handling.

SUPPORT OF RCRA REGULATION DEVELOPMENT

A study of nonhazardous power plant waste is being conducted by EPA/IERL-RTP for EPA's Office of Solid Waste to develop quantitative background information on the coal-fired electric utility industry's solid waste situation. The study was initiated prior to the determination that some coal ashes and FGD wastes might fall in the hazardous (now "special waste") category. Information from the study will be used by EPA in developing guidance documents to support implementation of the nonhazardous regulations under RCRA. A draft final report on this effort is currently under review.

Oak Ridge National Laboratory (ORNL) is conducting a program for EPA's IERL-RTP and Office of Solid Waste to evaluate the toxicity protocol proposed in the December 1978 announcement of potential hazardous-waste regulations under RCRA. This includes use of the extraction procedure, chemical analysis of the extract, and the biological testing described in the Advance Notice of Proposed Rulemaking (ANPR) of the announcement (23). Samples of fly ash, bottom ash, and FGD waste have been tested by ORNL under this program. None of the samples proved to be hazardous by the definition of the protocol. However, the number of samples tested was inadequate to establish a trend. The final report on this effort is being prepared.

EXTRACTION PROCEDURES

ORNL has also participated in the American Society of Testing Methods (ASTM) round-robin series of tests for evaluation of three extraction procedures—the EPA-proposed method and two alternative methods (Methods A and B) proposed by ASTM. Several coal ashes and FGD wastes were tested under this project. Only one sample—a bituminous coal fly ash—failed the toxicity criterion for selenium for all three extraction procedures. The same sample also failed the criterion for arsenic using the EPA extraction procedure and ASTM Method B, which is similar to the EPA procedure (i.e., an acetic acid leach is used) (24). Testing results from the other laboratories are currently incomplete.

The largest and most significant effort being undertaken in support of the RCRA regulation development is expected to get under way in the fall of 1979. This 2-year, multimillion dollar study is being conducted to provide sufficient data and information to define the appropriate RCRA standards for storage, treatment, and disposal of coal ash and FGD waste from coal-fired power plants.

General performance standards under RCRA Section 4004 are expected to be promulgated in September 1979. Once those standards are promulgated, RCRA Section 1008 guidelines more specific to certain types of disposal practices or certain types of industry waste may be issued. General performance and design standards under RCRA Section 3004 were proposed in December 1978 and are expected to be promulgated in December 1979. The proposed rulemaking for Section 3004 lists coal ash and FGD waste as "special wastes" (see "Present Regulatory Framework," above). This study will provide the data necessary to promulgate the guidelines under Section 1008 or the standards under Section 3004 applicable to utility waste.

STUDY METHODS

In performing the study approximately 16 full-scale waste-disposal sites will be selected, representing a cross-section of the coal-fired electric utility industry in terms of (a) types of wastes generated, (b) waste disposal site characteristics (e.g., geology, hydrogeology, climate), and (c) disposal methods used. Once the sites are selected, a full-scale evaluation will be conducted of each site, including waste sampling and analysis; hydrological studies; soil analyses; groundwater and leachate monitoring, sampling and analysis; and cost analysis. The data will be evaluated and recommendations will be made regarding the adequacy of the disposal method for meeting the performance standards contained in the Section 3004 and 4004 regulations. Control technology alternatives will also be suggested which will provide for compliance with the Section 3004 and 4004 regulations.

The disposal methods examined in the project will include the most prevalent methods used in the industry as well as those which are likely to represent the best control technology standards for disposal of coal ash alone and coal ash/FGD waste combined. About eight different waste types/disposal methods will be examined. Each specific disposal operation will be evaluated for its current and potential impact on the air quality and ground/surface water quality in the vicinity of the disposal site. The program will include testing each waste for toxicity, using the procedures required under RCRA Section 3001. In addition, Level I chemical and biological test procedures established by IERL-RTP for environmental assessment (EA) of energy-related processes will be used at one coal ash disposal site and one coal ash/ FGD waste disposal site. Level II EA procedures will be applied to all sites. Physical testing will also be conducted for potential leachate generation of the waste samples, as well as the capability for site reclamation. Each site will be evaluated for approximately 12 months. The study is expected to be completed by late 1981. Standards based on the study results are expected to be proposed sometime in 1982.

CONCLUSIONS

A major effort in the Interagency Energy/Environment Program is under way to characterize solid wastes from power plants and to assess and develop the technology required to minimize the potential adverse environmental impacts of these wastes. The program has achieved significant results in a number of areas.

Flue gas cleaning (FGC) wastes have been characterized physically and chemically; a variety of disposal options have been identified, along with detailed costs associated with the options. A program of monitoring full-scale commercial disposal operations is planned. Disposal of these wastes in coal mines is economically attractive and, therefore, is being investigated through laboratory and field tests. Evaluation of artificial reef construction using treated blocks of FGC wastes is also under way. Methods for achieving major cost reductions in FGC waste disposal have also been identified and are making their way into the process supply market. These include oxidation to gypsum and improved dewatering equipment. Results of these efforts are providing a technical data base for regulation of the disposal of power plant wastes.

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ARTIFICIAL FISHING REEF CONSTRUCTION USING COAL WASTES

(film)

AT-SEA DISPOSAL PROJECT

To cut imports of foreign oil, power plants are increasingly converting to coal use, thus exacerbating the already-acute problem of disposal of coal wastes. Flue-gas scrubbers remove fly ash and SO_x , producing flue-gas cleaning (FGC) wastes equal to 30 percent or more of the volume of coal burned, the percentage being a function of the amount of sulfur the coal contains. A large plant may burn 7,000 tons of coal a day, and it is estimated that by the year 2000 the nation's coal-burning power plants will produce over 100 million tons of FGC waste per year.

The northeastern United States, where land is scarce and costly, will not support the large landfills needed to accommodate the thousands of tons of sludge and fly ash produced daily. Many plants in this area, however, have access to the ocean, and assessments are being made of various methods of at-sea disposal of FGC waste. This assessment is a project of the Marine Science Research Center of the State University of New York at Stony Brook, cosponsored by the New York State Energy Research and Development Authority, the U.S. Environmental Protection Agency, the U.S. Department of Energy, the Power Authority of the State of New York, and the Electric Power Research Institute. The project is a large-scale pilot effort to demonstrate the feasibility of artificial fishing reef construction using treated blocks of FGC waste.

STABILITY AND LEACHING

In the early stages of this project, stabilized blocks of coal waste were laboratory-tested at Stony Brook. They were then submerged for 19 months as a small artificial reef in Conscience Bay in Long Island Sound off Port Jefferson, New York. The stability and leaching properties of the blocks in the sea water were of primary concern. Data were also collected on the type and amount of marine plant life growing on the blocks, and possible toxic effects on marine life. These preliminary investigations were very encouraging; the submerged blocks did not disintegrate, leaching of trace metals appeared to be minimal and harmless, and the plant life they attracted was uncontaminated by chemicals.

CONSTRUCTION

The next phase of the project involves the construction of an artificial reef in an approved site in the Atlantic Ocean off Saltair, Fire Island. This large reef will consist of approximately 700 coal-waste blocks, each 1 yard square and weighing 1 ton. The blocks will be fabricated in the spring of 1980 and, after emplacement late that summer, will be monitored for environmental effects and structural integrity for about 3 years. Once the engineering aspects of production and transportation of the blocks are developed, a cost analysis will be done to determine the economic feasibility of this method.

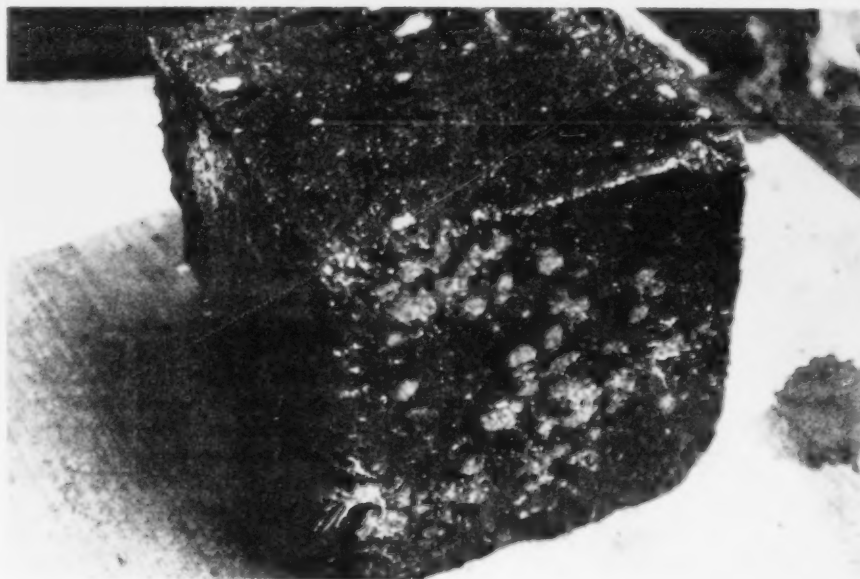
PROJECT SITE STUDIES

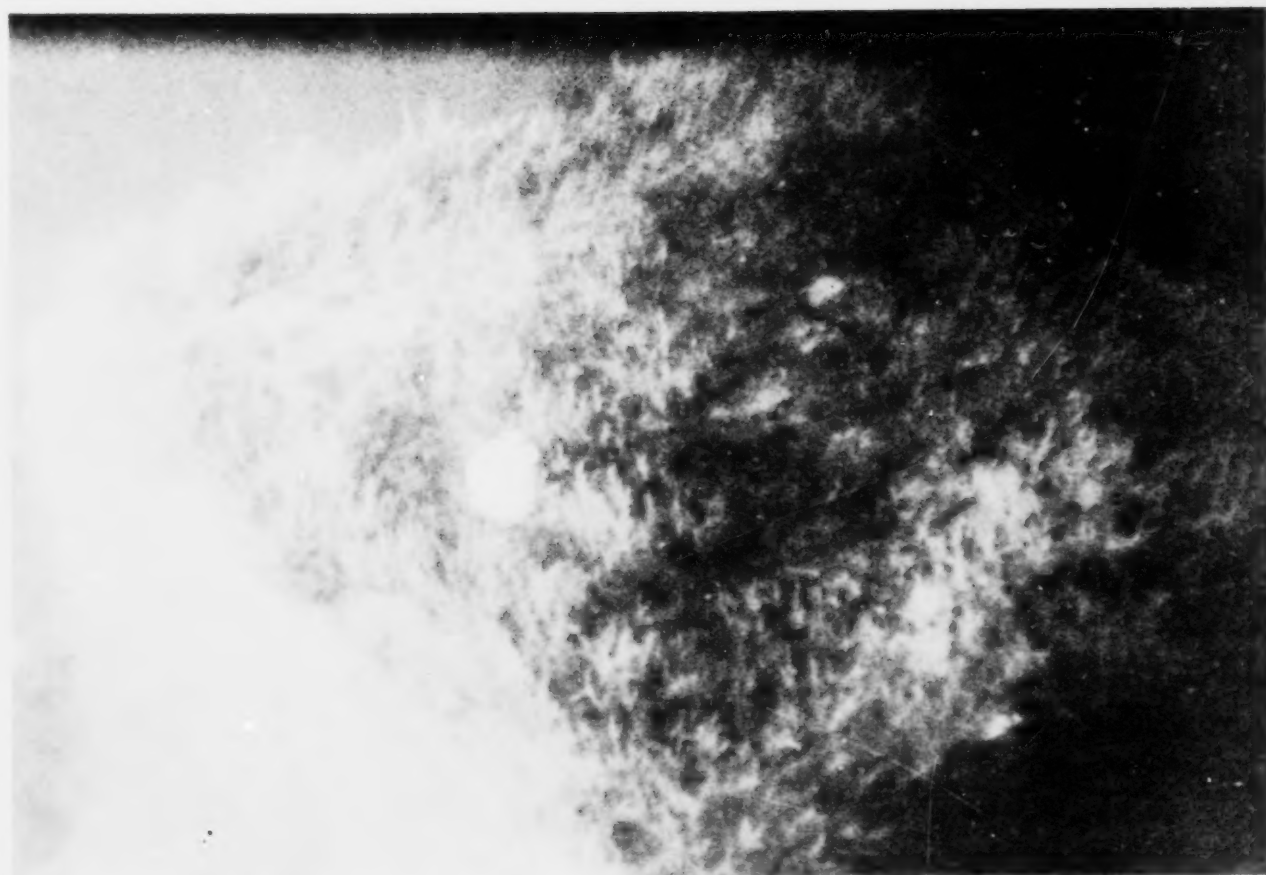
Oceanographic studies will define the environment of the project site before the reef is laid down. These studies will determine the physical and chemical properties of the water, including temperature, salinity, dissolved oxygen, suspended sediment, nutrients, and heavy metals. Samples of the phytoplankton and zooplankton communities will be taken, and divers will make surveys of both the project site and an existing artificial reef nearby. Laboratory studies of the chemical composition of the blocks and of their leaching properties will continue during this phase of the project.

TEST BLOCKS ANALYZED

Once the reef is in place, biological colonization of the surfaces of the blocks will be measured monthly. Test blocks retrieved from the reef will be analyzed to determine what sorts of organisms grow there. The materials of a fishing reef must attract the kinds of marine life that will in turn attract a variety of fish species. Control experiments at the reef site will be used as a basis for comparing the performance of the coal-waste blocks with that of other submerged objects, such as ship hulls, which are already known to attract plant life that attracts fish.

If the use of stabilized coal-waste blocks as artificial reefs proves environmentally and economically sound, the project will have demonstrated both an attractive alternative to landfill disposal of coal wastes and a means to increase the fish population in an area, and will have overcome a major obstacle to burning coal in power-generating plants and industries.





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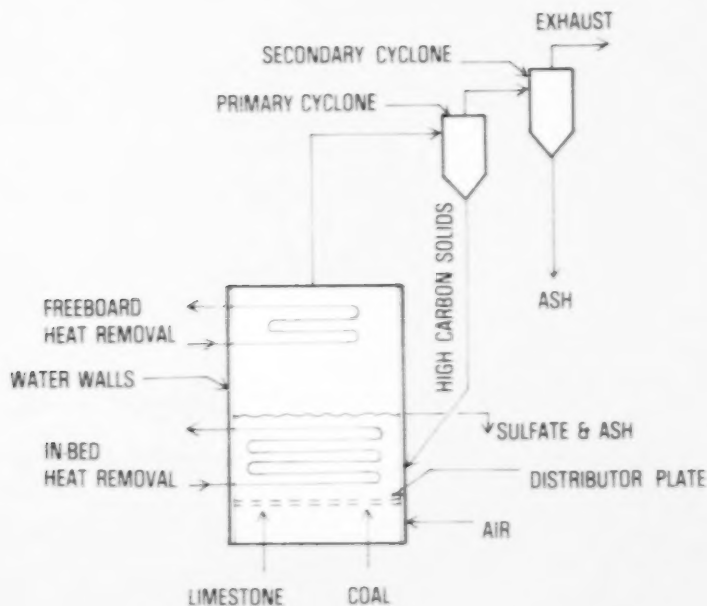


William T. Harvey

U.S. DEPARTMENT OF ENERGY FLUIDIZED-BED COMBUSTION PROGRAM

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The fluidized-bed combustion (FBC) of coal is a highly efficient process that uses a mixed bed of limestone, lime, sulfated lime, and ash. Figure 1 is a schematic drawing of the process. This process uses crushed coal (1/4" x 0)



AIR FLOW: 2 - 15 ft sec PRESSURE: 1 - 25 atm
TEMPERATURE: 1500°F-1600°F COAL SIZE: 1/4 in. x 0

SULFUR REMOVAL: $\text{CaO} + \text{SO}_2 \rightarrow 1/2(\text{O}_2) \text{CaSO}_4$

FIGURE 1—Typical fluidized-bed combustor

FBC FEATURES

bed of limestone or dolomite where combustion takes place. The coal and limestone are held in suspension by the injection of air through a distributor plate in the bottom of the combustion chamber. The limestone, in the form of calcium carbonate, is calcined to form calcium oxide which reacts with the SO_2 released during the combustion of coal. The result is a solid waste along with the coal ash. Fluidized-bed combustion, which takes place at a temperature between 1500° F and 1600° F, has several potential advantages.

This temperature range permits

- limestone to calcine,
- lime to sulfate,
- enhanced heat transfer rates, and
- generation of utility grade superheated steam,

while avoiding

- thermal NO_x generation,
- severe material problems,
- ash agglomeration and clinker formation, and
- slagging and fouling.

The FBC process can be designed to occur either at atmospheric pressure or at elevated pressure. The atmospheric pressure process, referred to as AFBC, is the least complicated. Combustion at elevated pressures must be coupled to an expansion turbine to recover mechanical energy for combustion air compression and to generate power from the hot pressurized products of combustion. This process is referred to as pressurized fluidized-bed combustion (PFBC). PFBC inherently produces less NO_x and is capable of removal of sulfur oxides to a greater extent than AFBC. The exact mechanisms of this process that result in these environmental advantages are not fully understood, but the data are conclusive. Several process configurations for AFBC and PFBC are being pursued by different organizations within the overall program strategy.

ECONOMICS

Many economic studies have been performed on FBC, but no commercial plant has been built and operated to provide actual cost data. Design studies show that when comparisons are made with alternative technologies, certain general conclusions can be made:

- Coal-fired power plants are much more expensive than oil- or gas-fired power plants.
- AFBC boiler pressure parts and the combustion chamber have the potential for being less expensive than those components in pulverized coal-fired steam generators.
- Elimination of a scrubber in a FBC power plant is a major cost saving, assuming a scrubber is required to meet emission regulations in a conventional plant.
- Equipment for handling sorbent and spent bed will add approximately one-half of the cost of the scrubber to the FBC power plant.
- Cost of a pulverizer is saved, but fan costs are substantially increased.
- AFBC systems which require dryers have this added cost and, if sized coal is required, this will result in increased operating cost.

COST ADVANTAGE

Cost studies comparing utility AFBC steam generators with pulverized-coal-fired steam generators equipped with stack gas scrubbers show a definite cost advantage for the AFBC units. In the industrial area, AFBC boilers are competitive today with conventional boilers with scrubbers. The major economic advantage of AFBC boilers is in their ability to burn a wide variety of coals and industrial wastes. This broadening of the fuel resource base for a particular plant, as well as the nation, will result in

lower fuel cost. PFBC power plants have an additional economic advantage. A PFBC plant will cost about as much as an AFBC plant, but its efficiency for power generation will be higher, 39% versus 35% for an AFBC plant. This results in a 10% fuel savings, which is substantial. The degree of hot gas cleanup required for a PFBC plant and the design of this equipment will materially influence the economics.

DOE PROGRAM STRATEGY

The overview of FBC strategy is to have a continuing staged technology development program to provide research data and an understanding of the phenomena, to test alternative process configurations, and to obtain experience with components and provide an engineering foundation for the technology. The staged technology program is a series of developmental and prototype units which will be scaled up to successively larger units for the purpose of engineering development and then to commercial prototype testing. The units will increase in size as development takes place from process development units (PDU's), to pilot plants, to industrial demonstration units and then to utility demonstration units. Units will become less flexible and closer to commercial systems as development progresses to larger sizes. The various elements of research and development program strategy are shown in Table 1.

TABLE 1
Overview of FBC strategy

-
- From applied research and exploratory development, estimate cost, performance, and scale-up factors to determine key technology development required for conceptual designs of commercial scale plants.
 - Design, construct, and operate PDU's for technology development to determine design performance parameters for fluidized-bed-combustors, gas cleanup and turbine modifications.
 - Design, construct, and operate pilot plants to obtain engineering data on processes, plant integration, and operability.
 - Design, construct, and operate engineering demonstration plants to develop and prove full scale equipment in late 1980's for commercialization in the 1990's.
 - Develop improved components and equipment to adapt demonstrated processes to other commercial systems.
-

INVOLVING INDUSTRY

Part of the overall strategy is to avoid an intermediate technology transfer by involving industry in the program, on a working basis, at the earliest opportunity. Thus, existing commercial, industrial, and utility users and equipment suppliers are closely involved in the DOE FBC program. The approach to implementing the strategy is as follows:

- Develop and refine the technology and engineering data for high risk elements for which federal funds are required.
- Design, construct, and operate technology development facilities with federal funds. However, provide and arrange for operation by industry to further define and refine the technology/engineering data base and to test various concepts/components.
- Design, construct, and operate engineering development systems. These systems would be provided by industrial suppliers at industrial and utility sites on a cost share basis.
- Obtain multiple qualified manufacturers to develop alternate approaches to minimize risk. This will ensure that future competition will exist and provide a broad manufacturing and engineering base for commercial implementation.

Development of FBC is progressing rapidly, and it seems probable that the first commercial contracts will be signed during 1979—most likely for small industrial units. Orders for utility FBC units cannot be foreseen clearly at present, but it seems probable that there will be none before 1987.

AFBC boilers in the size range of 1/2 to 2 MW_e equivalent have been operated at a high level of reliability. They could be suitable for space heating purposes. It is expected that industry will extend this product type to a size range of 2 to 10 MW_e equivalent. The DOE has funded several projects for demonstrating industrial units for institution and commercial space heating using bituminous and anthracite coal. For industrial process service, AFBC boilers of 10 to 50 MW_e equivalent will require high reliability before buyers will purchase these boilers. Buyers need to be assured of continued operation so that the remainder of their industrial process is not compromised by lack of steam continuity.

BOILER MARKET

A commercialization study task force, one of several commissioned by the Undersecretary, examined the AFBC industrial boiler product and market. This study concluded that the large industrial AFBC boiler was ready for commercialization. It also found that a market existed which held adequate promise for substantial additional coal use within the next decade. Industry acceptance of AFBC boilers will require resolution of the following uncertainties:

- Adequate technical and environmental performance.
- Operating reliability and system maintainability.
- Dependable basis for cost.

A Program Opportunities Notice (PON) was issued to obtain industrial AFBC boiler units to meet the above requirements. The results of the program that should result from this PON would complete the development of AFBC for industrial, institutional, and commercial applications. The continued development of a technology data base built on a development program will be needed until these systems are mature and adequate industrial laboratories are operational to supply industry's needs.

IMPEDIMENTS

Commercialization of FBC has major environmental and socioeconomic impediments to overcome. Some of the problems are common to all coal utilization technologies. Briefly, they are as follows:

Environmental Impediments

- Solid waste disposal
- Uncertain future standards for SO₂, NO_x, and particulates
- Possibility of new regulations, fine particulates among others
- Heat rejection

Socioeconomic Impediments

- Plant siting delays and costs
- Coal mining, coal transport and distribution

Either AFBC or PFBC can be used in utility and very large (over 50 MW_e equivalent) industrial applications. AFBC utility systems can make use of the AFBC industrial technology as a data base. The question arises as to which is the most appropriate technology for utility services. There are at least three options:

- Conventional AFBC

- Advanced AFBC, such as the staged fluidized-bed combustion, fast fluidized-bed, or other systems of advanced design
- PFBC

An AFBC development program will require at least six (6) years before even the smallest utility scale plant could be demonstrated.

Three levels of risk for PFBC technology are based on the inlet temperature of the gas turbine with the higher temperatures offering the advantage of higher system efficiency.

- High temperature/high risk
- Medium temperature/medium risk
- Low temperature/low risk

HIGH RISK

The original PFBC concepts of the early 1970's were those based on gas turbines operating at 1650°F blade temperature (based on clean fuel) with PFBC combustors. This PFBC temperature favors high combustion efficiency and high SO₂ removal. This is a high risk approach because of potential problems with fouling, erosion and corrosion; and a development program of substantial magnitude and time could be required.

An intermediate approach to PFBC/gas turbine arrangements is being pursued by a consortium headed by American Electric Power Company (AEP). AEP's proposed plant would include a gas turbine originally designed for use with crude and residual oil and designed for a turbine inlet temperature of 1470°F. The system will be designed with the capability of lowering turbine inlet temperature to 1000°F-1100°F by use of an air by-pass from the compressor discharge to the turbine inlet.

LOW RISK

Power recovery turbines operating at an inlet temperature of about 1000°F have been used extensively with regenerator off-gas from catalytic cracking operations. Such turbines could be used in PFBC cycles in combination with heat recovery units suitable for reducing PFBC gas temperature from 1600°F to 1100°F. Power recovery turbines are available commercially, and they operate at a lower pressure (3.0 atm vs. 12 atm) and at a lower gas velocity (1000 fps vs. 1500 fps). Particulate loadings are typical of the efflux from a PFBC combustor, and the effluent size distribution is not unlike that of PFBC. However, cat cracker gases do not contain the alkalis or alkali sulfates or a variety of ash mineral matter (such as quartz and ferrosilicates) found in coal combustion products. At temperatures below 1150°F, the corrosive effects of alkalis are believed to cause damage at a substantially reduced rate, permitting over 25,000 hours of service. The fouling (deposition) tendency of coal ash in such machines is not known, but conventional techniques for removing deposits from gas turbines in PFBC systems are expected to be adequate. The power recovery turbine (turbo-expander) is a rugged machine and, combined with the less severe operating conditions, is an approach that offers substantially reduced technical risk. The low temperature approach would provide a turbocharged boiler that would be compact, potentially lower in cost, and environmentally cleaner than alternative combustion systems.

The major factors affecting the technical and cost performance of FBC systems are combustion efficiency, sorbent performance, materials durability, and equipment size and complexity. All of the foregoing are highly dependent on design and operating variables including coal and sorbent type, operating temperature, and fluidizing velocity.

PROCESS OPTIMIZATION

Much information exists on the relationships among operating variables and performance, but the FBC process has not been optimized. Improvement of the competitive advantage of FBC will require continuing R&D support, particularly if technology implementation is to proceed from small industrial applications to large industrial and utility applications. Obviously, as unit capacity increases, costs become increasingly important so process optimization continues to be an important element of the RD&D program. For example, combustion efficiency (carbon utilization) in

AFBC depends on a host of factors, the most important of which is fluidizing velocity. Fluidizing velocity establishes the amount of carbon elutriated from the bed and the need for its recovery and further combustion; in addition, fluidizing velocity is directly proportional to bed size (area). At higher velocities of 8-12 ft/sec, 10-15% of the coal carbon is elutriated from the bed and must be recovered and returned for additional burning in a separate cell (carbon burnup cell). At lower velocities of 3-5 ft/sec, a carbon burnup cell is not required. Higher velocities would be preferred because they permit more compact steam generators and the shop fabrication of units with greater capacity. Capacities of shop fabricated units are expected to be 300,000 lb/hr of steam for high velocity systems; at low velocity, unit capacity of shop fabricated boilers likely could not exceed 150,000 lb/hr.

GENERATOR SIZE

Figure 2 shows the relative size of three steam generators of 550,000 lb/hr capacity designed for various fuels. As can be seen, the coal-fired AFBC unit is similar in size to an oil-fired unit. The AFBC unit is smaller than a conventional coal-fired unit because of the AFBC's higher volumetric heat release rate, typically 100,000 Btu/hr-ft³ as compared with 20,000 Btu/hr-ft³. Even at the lower velocities, the AFBC unit still would be significantly smaller than the conventional coal-fired unit.

Another area of importance in AFBC technology is fuel distribution within the bed. Fuel distribution and bed mixing greatly influence carbon utilization and the behavior of heat exchangers immersed in the bed. In the latter case, fuel distribution must be even to avoid localized oxidizing and reducing zones which could cause severe materials problems. Up to the present time, the fuel distribution problem has been solved by introducing small quantities of fuel per unit area of bed, and it has been found necessary to provide a feeder for every 10 ft² of bed area. This requires many fuel feeders or splitters for distribution. The large number of fuel feeding points and the complexity of the feed system are areas that represent an opportunity for process equipment improvements. Development work is being performed to simplify the feed system using a spreader-stoker feeder which throws the coal onto the surface of the bed. This approach, shown in Figure 3, is to be tested in the industrial steam generator at Georgetown University. The steam generator is shown in Figure 4.

PROCESS OPTIMIZATION

Fuel feeding/distribution and fluidizing velocity also are important with regard to environmental performance. Thus, after considering the complexity of the many process and design interrelationships, it is apparent that process optimization is required if AFBC technology is to become technically and cost attractive in larger size applications. In addition, the bed profiles of individual species must be known together with their creation/destruction mechanisms in order to have a basis for emission standards. The possibility of staged FBC exists with reduction of NO_x as a goal. Coal

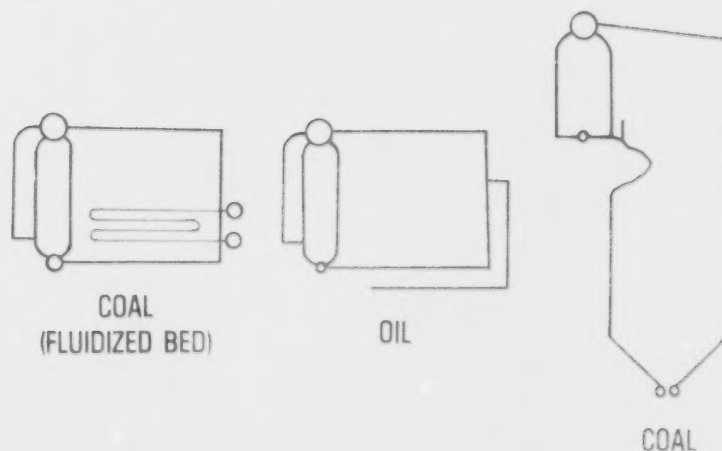


FIGURE 2—Comparison of 550,000 lb/hr units

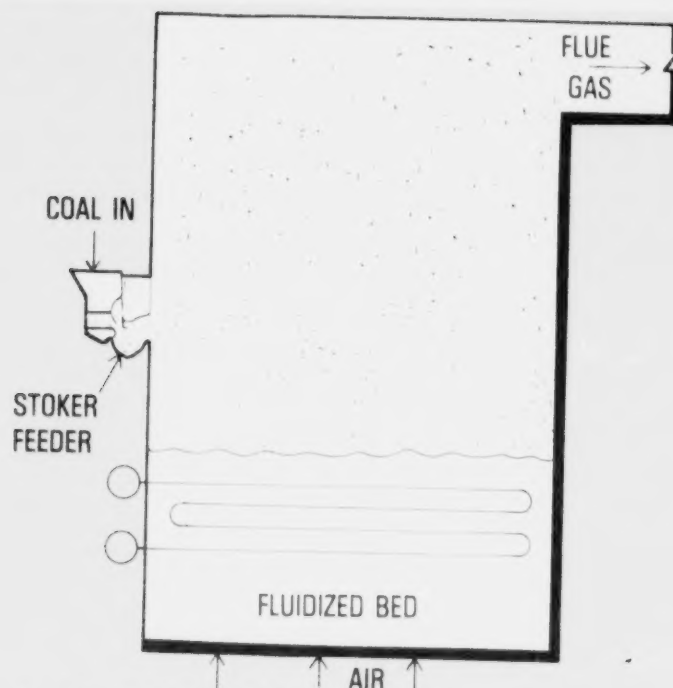


FIGURE 3—Conceptual arrangement of overfeed FBC

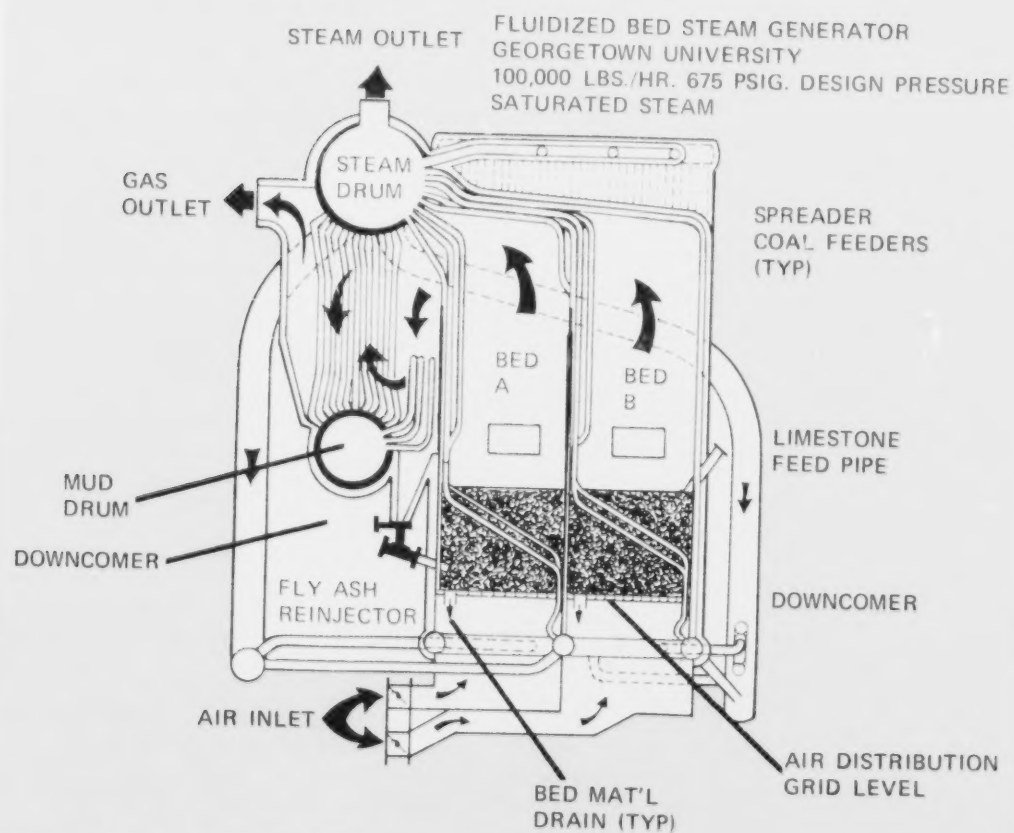


FIGURE 4—Industrial fluidized-bed steam generator, Georgetown University

feed, ash removal, and flyash recycle systems need to be brought to the point of practical operation. Baghouse or precipitators must be engineered for the high calcium flyash.

In PFBC, fluidizing velocity and fuel distribution are not as important as in AFBC—pressurization dramatically reduces the size of the combustor. The area of greater uncertainty is the gas cleanup necessary for acceptable gas turbine life.

LOW-TEMPERATURE APPROACH

The technical risk associated with gas turbines in PFBC cycles is a function of turbine inlet temperature. The PFBC cycle is flexible in regard to the operating temperature of the gas turbine which is related to turbine durability/operability. At a turbine inlet temperature of 1600°F, the highest now anticipated for PFBC, it is expected that cycle efficiencies of 41% or greater can be achieved. Operation at this temperature level also involves higher technical risk with the gas turbine. In low-temperature (1100°F) cycles, technical risk is minimized, and cycle efficiency still is a respectable 34-35%. At the intermediate turbine temperature of 1475°F proposed by AEP, commercial operation is predicted to give an overall plant efficiency of 39.4%.

HIGH-TEMPERATURE APPROACH

The high-temperature, high-risk approach represents a potential improvement of 6 or 7% in cycle efficiency compared with the conservative, low-temperature approach. Thus, there is substantial incentive to develop the technology to the stage that the higher temperature turbines can be utilized. Attainment of this goal would result in substantial fuel savings in PFBC plants, equivalent to a reduction in heat rate from about 10,000 Btu/kWh. Achieving this goal, however, will depend on future developments in technology related to gas turbines and gas cleanup. Some of the R&D options being pursued or considered for these components include:

- Improved resistance of turbine materials to corrosion by
 - blade cladding materials
 - blade cooling
- Advantages of larger scale turbines (and blades) with respect to blade erosion. Larger blades are expected to experience less erosion because their larger turning radii will cause less deflection of particles from the flow streamlines.
- Removal of turbine deposits by use of cleaning materials of controlled abrasivity
- High-efficiency particulate collectors of the centrifugal and mechanical filtering types
- Removal of corrosive alkali metal vapors from the gas by chemical "getters" such as diatomaceous earth and activated bauxite

DOE'S RD&D PROGRAM

The current AFBC and PFBC programs consist of several projects for technology development and for engineering demonstration while some are planned for commercial demonstration. The programs initially involve technology development by investigations in successively larger units followed by engineering and commercial demonstration. The AFBC program includes several projects, listed in Table 2, to develop the technology base needed for both utility and industrial applications. These projects include the process demonstration unit at Alexandria, Virginia, for exploratory development; the Component Test and Integration Unit at Morgantown, West Virginia, for technology optimization and component development; and the 30 MW_e pilot plant at Rivesville, West Virginia, for engineering development.

DOE efforts in AFBC industrial applications draw on the experience of the industrial participants and are a natural outgrowth of the technology development program. The industrial applications projects include unit sizes up to 100,000 lb/hr equivalent steam generating rates and are listed as follows:

- Conventional AFBC

- Georgetown University Boiler for Saturated Steam
- Great Lakes Naval Training Center Boiler for Superheated Steam
- FluidDyne Process Air Heater
- Exxon Process Heater for Crude Heating
- Anthracite Applications Projects
- Oak Ridge National Laboratory Coal Combustor for Cogeneration
- Advanced Concepts
 - Battelle Fast Fluidized-Bed Boiler
 - Wormser Staged Fluidized-Bed Combustor

AFBC INDUSTRIAL APPLICATION

Demonstration of conventional AFBC in industrial application will be achieved by 1983. This engineering demonstration is certain to precede that of advanced concepts. Boiler suppliers participating in the program are expected to proceed with commercialization of the demonstrated technologies. Demonstration projects will be undertaken to accelerate widespread commercialization of large industrial units and are expected to confirm the economics of AFBC by late 1980's.

AFBC UTILITY APPLICATION

Commercialization of AFBC for utility applications is expected to follow commercialization in the industrial sector because of the scale which is involved. The 30 MW_e pilot plant shown in Table 2 will confirm the process design, while the 6 MW_e CTIU will provide information for process optimization and component development and testing. The coal feed test apparatus and boiler material test apparatus projects are anticipated to provide the necessary input to design engineering demonstration units for AFBC utility applications. The Tennessee Valley Authority is likely to undertake

TABLE 2
AFBC projects and functions

Project	Function
Bench/PDU	Provide data for technology base and design data for larger units.
6 MW _e CTIU	Further broaden technology/engineering base, test components, optimize system configuration for stacked cells, investigate dynamic behavior, provide "hands-on" access to private sector.
30 MW _e Pilot Plant	Evaluation of large beds for performance regarding combustion efficiency and pollution control.
Utility Demonstration Plant	Demonstrate FBC technology in utility environment on a large scale unit.
Coal Combustion for Cogeneration	Demonstrate feasibility of externally-fired heater for closed cycle or externally fired gas turbines for total energy systems.
Industrial Demonstration Plants	Develop wide base of AFBC designs for industrial/institutional applications covering boilers, steam generators, process heaters.
Anthracite Culm Application	Initiate FBC program for culm and anthracite and coal refuse utilization with industry participation.

the AFBC engineering demonstration unit. By the early 1990's, TVA should have this project completed and it likely will be followed by a commercial utility project.

The technology and engineering development projects for the PFBC program are listed in Table 3. The major projects include the Curtiss-Wright (C-W) small gas turbine (SGT) for technology development, the C-W/pilot plant and the IEA/Flexible Test Facility for engineering development using current state-of-the-art gas turbines.

FBC WASTES

Although substantial quantities of waste from FBC processes are not predicted for nearly a decade, the AFBC and PFBC processes will be attractive to potential users only if acceptable waste disposal or utilization methods are developed. Therefore, commercial implementation of FBC must be preceded by meaningful studies on waste disposal and/or utilization. The latter activity is important since few industrial facilities located in urban areas have the means to dispose of FBC wastes. At best, the FBC process would be enhanced if solid wastes could be used as a raw material, providing revenue to the FBC user; at the least, the waste must be removed from the FBC site at reasonable cost and disposed of in an environmentally acceptable manner. So, solid waste research is being conducted concurrent with other FBC technical activities to investigate thoroughly the utilization of FBC waste products in agricultural and other applications.

TABLE 3
PFBC projects and functions

Project	Function
Bench/PDU*	Provide data for technology base and design data for large units.
13 MW _e Pilot Plant	Design, construct, operate, and evaluate PFBC air heater cycle for scale-up to utility size.
IEA PFBC Facility	Perform research on coal combustion, heat transfer, SO ₂ sorption and fluidization characteristics. Gas volume matched to 10 MW _e gas turbine. Clean-up requirements for gas turbine not yet determined.
Cycle Development	Develop/evaluate alternative PFBC cycles for commercial implementation.
Engineering Demonstration System	Verify PFBC concept, verify design data, and generate commercialization data.

* Includes Exxon Miniplant, CPC Granular Bed Filter, Curtiss-Wright SGT/PFB Unit, and CURL/Leatherhead Research Facility.

panel discussion



**CONTROL TECHNOLOGY PANEL DISCUSSION
WITH QUESTIONS AND ANSWERS**

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MR. PRINCIOTTA: The recently promulgated utility New Source Performance Standard (NSPS) calls for 70 to 90 percent sulfur oxide control, with a minimum of 1.2 pounds per million BTU from fossil fuel-fired power plants. It calls for 0.03 pound per million BTU particulate standard and a slightly more stringent nitrogen oxide standard of 0.5 to 0.6 pound per million BTU as opposed to the current 0.7 pound. This is perhaps the most important standard relating to coal combustion ever set. The first question before this panel this morning involves the implications of the new standard with regard to commercial selection of control technology and as regards research, development, and demonstration needs and goals.

MR. SHAPIRO: The regulations will have a definite impact on coal use. They are certainly more severe than the current ones, but they will also allow for selection of control technology. No particular solution or technology will be applicable for all situations. The technology will be very much a function of the particular site; the geographical location; the state regulations, which may be more stringent than Federal regulations; the availability of various coal supplies; and the sulfur content of the coal. In each application, utilities will have to find the optimum solution to their control problems, be it, for example, the use of coal preparation, the continuation of limestone systems, or the use of dry scrubbing approaches, which show so much promise now. It is very important that for each situation a choice, based on a particular location and on economics, be available to the utilities.

MR. ELDER: It is fortunate that the ceiling was set at a level that keeps most of the coal that is available for utilities and other uses in the picture for continuing energy production. The break point on the regulation is reasonable in that it allows the use of low sulfur coals with degrees of removal efficiency that are reasonable for this new dry scrubbing technology. The combination of coal preparation and coal cleaning with dry scrubbing could be quite important for utilization of the mid-range sulfur coal. So, in effect, the new regulations have not closed out the options. With one exception, they keep all of them open. The very high sulfur coals will require more than 90 percent removal efficiency. This will require something other than the lime and limestone scrubbing technology that is now the leading method.

As to the reasonableness of the removal efficiencies, we know that the 90 percent level established is certainly achievable, at least on an instantaneous basis. The main question becomes, how long can we continue to meet 90 percent removal during prolonged operation? It is a risk factor. We trade off removal efficiency versus reliability. To maintain 90 percent, particularly over an extended averaging period, will require fairly close control of the operating characteristics of the scrubber. Matching up the rate of addition of absorbent with the SO_2 concentration in the flue gas will be quite important in meeting the level. In the utility industry, particularly in the application of the technology at this stage, the control of the ratio between absorbent and SO_2 has not been as good as it will need to be to get 90 percent on a reliable basis.

DR. MCKINNEY: As far as a commercial venture is concerned, in the near term, probably until 1987, lime and limestone scrubbing are what is available. We are therefore going to produce sludge for several more years. Some of EPRI's funds are going into developing advanced regenerable systems or systems that make gypsum, but at this

time, for the utility industry we represent and that funds us, the near-term option is lime and limestone. This is not necessarily the most beneficial option, and therefore a lot of our money is going into other R&D projects. There will certainly be some room for choice in the future, but right now a utility is unlikely to opt for any process but lime or limestone; the other technologies are just not sufficiently developed.

QUESTION: *The old utility boiler systems used multiple retard underfeed stokers and multiple boilers so that they would have redundancy. With similar built-in redundancy, would there be such concern about maintaining the 90 percent SO₂ removal reliability?*

RESPONSE (Mr. Elder): The 90 percent was removal efficiency rather than reliability. Since the trend is toward greater redundancy, more spared equipment, the reliability is improving. The question is one of cost. The degree of cost must be considered; the sky is not necessarily the limit. Perhaps we neglected to address the R&D needs. When we spoke earlier of forced oxidation, the point was not stressed that the conversion provides gypsum that can be recirculated back to the scrubbing system. That is a key process step that improves the operating characteristics and reduces the scaling and puddling potential. One of the significant factors in the Japanese success is that they use forced oxidation and recycle the gypsum seed back to the scrubber. This is the direction in which the EPA program is heading, and it is the right direction, as is DOE's attempt to accelerate development of forced oxidation work. It will be very important for the future of lime and limestone scrubbing.

Another important area that needs improvement is instrumentation, the measuring devices used on scrubbing systems, not only to measure gas concentrations but to measure gas flow rates, slurry flow rates, and pH so that we can have better control of the process chemistry.

The last area that needs work is mechanical components. Provided we have proper controls, we no longer worry much about process parameters. The real problems with reliability, with keeping systems in operation, are with mechanical components. In our R&D program we have not done a good enough job of selecting the best equipment components, particularly in areas of control gas and liquid flow, so that we can make recommendations to equipment suppliers that would give us more reliable systems. Additional work is needed in this area.

RESPONSE (Dr. McKinney): Particulates evoke similar concerns. Depending on how the environmental control agencies monitor the particulate standard, the utility industry, in order to meet the standard on a continuous basis, is probably entering a new era in regard to electrostatic precipitators. We do not know well the performance and reliability of precipitators. Since we have never had the continuous particulate monitors, we are looking at something new.

Because we try to do things on an economic basis, we have had some studies done that indicate that baghouses are possibly the most economical particulate control devices. We do not have experience with baghouses on large pulverized coal for boilers. We certainly do not have experience on high sulfur coals. From the Arlington station in Texas there is some minimum experience on lignite or low sulfur coal. Because we do not have the requisite experience, we have to caveat the economics of the baghouse situation with the precipitator.

MR. PRINCIOTTA: This conference, and in particular this session, has thus far focused primarily on conventional combustion, pulverized coal, combustion of coal, utilizing combustion modification for NO_x control and flue gas cleanup, particulate and sulfur oxide control. The exception was the fluidized bed presentation. What do the panelists think about the viability and commercial status of emerging coal to electric technologies, such as fluidized bed combustion, low BTU gasification, coal liquids, and possibly even some of the softer noncoal technologies?

MR. SHAPIRO: The advanced technologies will not affect the utility and industrial sectors to any great extent until the 1990's at the earliest. The one exception to that might be the industrial applications for atmospheric fluidized bed combustion, which

seems to be moving rapidly toward viability now, with the possibility of commercialization in the early 1980's. Advanced technologies, such as pressurized fluidized bed combustion, combined cycle systems, low BTU gasifiers, MHD, and carbonate fuel cells, deal with the problems associated with meeting environmental regulations that will be enforced at a later time. They also focus on improved efficiency, which will result in lower total emissions and lower costs for electricity. It is too early to say that there are clear winners among the advanced technologies, so we are taking parallel paths in developing them, looking at them as alternative energy sources that will impact the marketplace sometime in the 1990's.

MR. ELDER: From a utility viewpoint, there is now no alternative to conventional combustion with flue gas desulfurization. The most cost-effective way to meet both the proposed New Source Performance Standard and the existing standards is by use of conventional technology. The nearest-term challenge will be with fluidized bed combustion because it is further developed. TVA is in the midst of a design phase for a 200-megawatt atmospheric fluidized bed demonstration that promises to be an economic and technical competitor to conventional technology. Beyond that, I see nothing on the horizon that can help the economics or the environmental considerations for the utility industry. There are a couple of sidelines that may be important, such as liquid fuel or refined coal. There could be an alternative for use of distillate oil in gas turbines, used primarily for peaking power. As a higher proportion of the demand shifts toward nuclear, there will be more need for short-term peaking power, and gas turbines are likely to serve that need. An alternative to distillate oil for gas turbines is a real need in the utility industry.

DR. MCKINNEY: Based on economic evaluations of technologies by the Electric Power Research Institute, the conventional coal-fired system, which we know the cost of because we have built some, is running about 50 mills per kilowatt hour instead of 35. Pressurized fluidized bed combustion, atmospheric fluidized bed combustion, and coal gasification with a combined cycle system, all involve about the same generating costs, 50 to 60 mills per kilowatt hour.

We have recently started another economic evaluation of the advanced conventional system. There is probably still a lot of R&D to do on the advanced conventional system, and we probably have a better handle on the costs of the conventional system. We are trying to get some optimistic data on the costs of the conventional system to compare with estimates for the emerging technologies, with an end in mind of possibly advancing the state-of-the-art in the conventional pulverized coal-fired boiler as another emerging technology. We have also done some evaluation of solvent refined coal. So far, our projections on the generating capacity in this country are inconclusive.

MR. SHAPIRO: Although my area of expertise is not the softer technologies, the projection for them is that they will be viable only when they are economically competitive, which ties in closely with local situations. If people can get a return on their investment in the use of solar, insulation, or conservation measures for a particular application, they will pursue it. The Government has made it easier through tax rebates and tax credits. The so-called soft technologies are not the total answer, certainly not for electrical generation in the near term. If, for heating applications such as hot water, these technologies become economically worth people's investment, they will definitely make a contribution; anything saved through solar use or conservation diminishes the requirements for oil- and coal-fired electric generation.

MR. ELDER: The soft technologies are a supplement to, not a replacement for, conventional power, specifically electric power, even though TVA has quite an aggressive loan program encouraging conservation through insulation. They give financial assistance to people to install solar demonstrations as test units in their homes, particularly for water heating. There are certainly supplementary technologies that will eventually contribute, although probably in a minor way, to saving energy for additional production of electricity. Every little bit helps, and we have to be more conscientious about looking at every piece of the puzzle, so that eventually we can put it together to advance everyone's interests, including those of us in the power-producing business.

DR. MCKINNEY: We have a solar program, but our projections do not show solar development contributing much for a long time. Geothermal may contribute 2 or 3 percent, but solar will contribute somewhat less than 1 percent. This is partly because a new technology takes 30 to 35 years after inception to become commercial, and we do not see solar becoming commercial before that time.

COMMENT: While we have to have block power for electrometallurgical and electrochemical operations, cities, community operations, and major institutions, there is in solar a strong element of recreation, play, and learning for the individual householder and apartment dweller that we tend to overlook. People will invest time and money in solar, even though it may not be economical to do so. Solar technologies developed over the past 20 to 30 years have been used in the sun belts of the world.

COMMENT: The International Solar Energy Association celebrated its 25th anniversary recently in Atlanta, Georgia. Based on what I heard there and 25 years of personal involvement in solar energy, I agree that solar electric power is not going to make much of a dent before the year 2000. But solar heat is here now, and that is where the application is. Solar energy is free, but it is expensive to collect it. Once it is collected, it does not make much sense to throw away most of it by trying to convert the remainder to electricity. The materials associated with solar energy technology, whether they be photovoltaics or thermal conversion systems, are energy intensive. It is hard to think of a more energy-intensive material than silicon, unless it is enriched uranium, steel, glass, copper, or aluminum. All these are produced in very energy-consuming industries using hard technology. There is nothing soft about any of them.

QUESTION: *When did research begin on the control technology relating to coal?*

RESPONSE (Mr. Elder): Some of the fundamentals date back to our first knowledge of the basic chemical reactions and mechanical components. TVA's activity in the area of flue gas desulfurization began in the early 1950's, when they built their first coal-fired power plant. Prior to that, there had been one commercial installation in England, in the 1930's, which was shut down in the 1940's. Although TVA's activity began in the early 1950's, the recent comprehensive program with full Federal support did not begin until the late 1960's.

MR. PRINCIOTTA: We have heard a lot about new developments in control technology for coal. Which seem to be the most promising or exciting technologies relating to clean combustion of coal, with particular emphasis on those that might make an impact in the next several years?

DR. MCKINNEY: The advanced conventional coal-fired boiler and fluidized bed combustion are probably the most exciting technologies, and EPRI is funding a demonstration project with Texaco in southern California on the coal gasification combined cycle, which looks promising.

MR. ELDER: Although there are some exciting advanced technologies, conventional combustion appears to be the only near-term choice. In the conventional area, I am quite disappointed that recovery technology has not gained a higher status in the utility industry. Most of the technology is based on lime or limestone scrubbing and results in a throwaway product. This technology has received the bulk of R&D attention. The potential is certainly there for a recovery technology that will avoid the creation of another waste disposal problem while allowing recovery of a valuable resource. Perhaps it is not generally known that there is a projection for a shortage of elemental sulfur in this country by the turn of the century. Sulfur is a very important industrial chemical, the supply of which is affected by the energy used in its production. It is mined by heating water and pumping the water into the ground, melting the sulfur, and taking it out. The natural gas used for sulfur production has become quite expensive in recent years, which is adding to the cost of sulfur. At the same time, onshore deposits have been depleted and more and more sulfur is coming from offshore mines. These factors will combine to increase the cost of sulfur and therefore provide a greater incentive for recovery from coal combustion. In the next 20 years or so we should try to develop technology to recover sulfur from coal combustion. The

efforts being made have not been as extensive as is required to get acceptance by the industry.

MR. SHAPIRO: Apparently the use of additives such as magnesium and the adipic acids makes lime-limestone very promising, although some problems associated with the additives have to be considered. The closed-loop operation, sludge fixation, and forced oxidation are also looking extremely good.

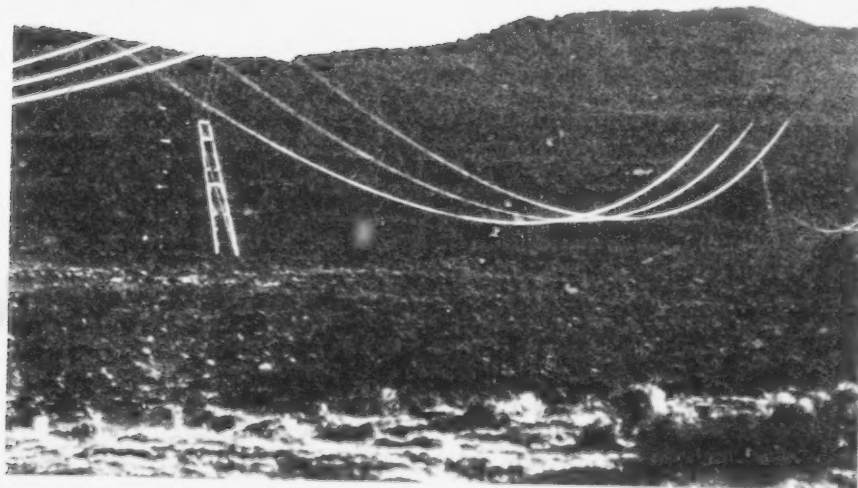
Six or seven advanced processes that appear very promising will probably have to be pursued in parallel. No one system will satisfy the requirements for all utility sites. The particular requirements of the individual utility, location of the site, state regulations, availability of coal, and disposal facilities will influence the choice of types of scrubbing necessary to provide the lowest cost system.

In regard to the regenerable systems to recover sulfur, even if the sulfur does not turn out to be a marketable product, the generation of the sulfur itself would result in a more easily disposed of waste product. The costs of disposing of pure sulfur versus some of the other sludges and materials will be less.

I would also like to reinforce the statement that instrumentation and process controls will be an extremely important area, and a lot of effort should be put forth in that direction. This is an area that our program in the Department of Energy will be focusing on. AFB will be expanding very rapidly in the near term, primarily in industrial applications. Possibly TVA will be sponsoring some development in the utility size applications, also.

MR. ELDER: The New Source Performance Standard virtually rules out scrubbers as a particulate control mechanism. That is disappointing because it seems foolish to spend money for big electrostatic precipitators when we could probably do the same operation in one device. If, in fact, we are stuck with both precipitators and scrubbers, we should work on putting the precipitator after the scrubber rather than before.

DR. MCKINNEY: In the advanced conventional fired plants, I assume that we are going to regenerable FGD and are not going to keep making sludge from now to eternity.



QUESTION: *Are the utilities informally involved in the R&D selection and structuring program to ensure that they will use the program you are working on?*

RESPONSE (Mr. Shapiro): One objective of the research and development of scrubber technology is to ensure that coal is a viable option and will be used. We must therefore involve the people who will be using the coal and will be purchasing the control technology systems. We expect to work very closely with them, and we anticipate cost-sharing between utilities and equipment manufacturers. Probably the most important aspect of the program is to ensure that the technologies developed result in commercialization and are actually used by the utility sector.

RESPONSE (Dr. McKinney): The Electric Power Research Institute represents the utility industry in R&D and has advisory committees that approve our projects. We also have working agreements and informal contracts with both DOE and EPA. The programs do come back to the utilities.

COMMENT: We have a program in Sweden with American Electric Power which is probably as advanced as TVA's program for AFBC. We are designing a combustor that will lead up to the commercial size PFBC in the 200- to 250-megawatt range. We hope to build a demonstration plant on the AEP system, combining a 70-megawatt gas turbine and combustor with an existing 110-megawatt steam turbine. We believe that this has a better potential for sulfur retention, NO_x suppression, and lower cost. It will also lead to more large-scale cogeneration for the large industries, such as petroleum, chemicals, or eventually district heating applications. We see a potential for much higher electricity-to-heat output with these systems than we can get with either conventional steam back pressure systems or AFB back pressure systems. We expect to see plants operating no later than 1984, although AEP has not made a formal commitment to start on the hardware; but we are far into phase 2 of the program, which involves very detailed design of the equipment. So far this is being done on a shared-cost basis with AEP, but we hope in the next round to get contributions from other groups as well.

MR. ELDER: There are certainly potential advantages to the pressurized system, but the viability for the atmospheric unit is closer.



questions & answers

Dr. Edwin S. Rubin
Carnegie-Mellon University

Jean B. Cornelius
Avon Lake League of Women Voters

Doc Hodgins
Friends of Eastport

J. Lee Krumme
Vinings Chemical Company

QUESTION

With respect to industrial applications of fine particle control in solid and liquid waste effluent, can we talk about applicability, availability, cost of technology, and R&D programs envisioned or under way?

RESPONSE: Dr. Leslie E. Sparks (EPA)

The control technology used for industrial boilers is fabric filters, which are efficient enough to meet the standards. The novel precipitator will probably be applicable to the industrial boiler after the technology is demonstrated. We do not, however, have a specific program aimed at the industrial boiler market.

QUESTION

In the area of FGD wastes, what are some of the liquid waste FGD systems prevalent in industrial applications?

RESPONSE: Mr. Julian W. Jones (EPA)

Although the question is aimed at liquid waste, some specific problems concerning solid waste in the industrial area must be addressed because of the current smaller-scale situation. These problems have been identified in the past year. The long-range effects of the use of coal are a subject for future work. As to liquid wastes, dry scrubbing using a sodium base material is probably the most imminent happening. The problems there would be quite similar, and the technology associated with disposal of sodium waste from the dry scrubbers would or could be applicable to the sodium scrubbers at the industrial scale.

QUESTION

Is the fluidized bed combustion process discussed today similar to the Akron, Ohio, process that mixes coal with garbage?

RESPONSE: Mr. William T. Harvey (DOE)

The fluidized bed combustion process can utilize any combination of combustible materials, and the combustibles can be burned concurrently or serially.

QUESTION

Landfill has been the preferred method of fly ash disposal for some time. Does anyone know, at this time, what leachate goes into the groundwaters from it?

RESPONSE: Mr. Jones

This will be a part of a study we will be doing in support of the regulations. The practice of landfilling with fly ash has been going on for some time, but we do not have much information about groundwater contamination yet. Studies have been done as a part of our program, some of them conducted by TVA, about possible groundwater contamination, but the results have not yet been issued.

QUESTION

There are less traditional pollutants associated with coal which have not yet been mentioned here. Could the speakers discuss the latest research on radioactive nuclides, for example, and on carbon dioxide, selenium, mercury, nickel, and cadmium? Some very good and timely studies have been done. What effect will these pollutants have?

RESPONSE: Mr. Frank T. Princiotta (EPA)

There is absolutely no question that the ambient concentration of carbon dioxide has increased as a result of fossil fuel combustion. What the concentrations will be over the next two decades and how meteorology will be impacted are being studied in a major, multimillion dollar DOE program aimed at eliminating some of the uncertainties and identifying the ultimate implications of increasing amounts of CO₂. Every time anything burns, be it gasoline in an automobile or coal in a power plant, carbon monoxide is generated. It poses a long-range problem that will need a long-range solution.

EPA has an active Conventional Combustion Environmental Assessment program. Its goal is to ascertain some of the untraditional, currently unregulated problems associated with coal. Some work has been done on radionuclides, and more in the area of heavy metals from coal and residual oil as well. Mercury, selenium, cadmium, and other heavy metals have been studied. The results to date have been inconclusive. What is clear is that ambient air impacts of coal burning, relative to these

heavy metals, are rather trivial; there are very small concentrations in the air. That is not to discount it as an environmental problem. Some of these metals, such as cadmium, can be concentrated by plants and end up in the food chain and in man via a mechanism other than breathing. Preliminary results suggest that heavy metals, at least from coal or fossil fuel combustion, are probably not a direct ambient air quality problem. Work continues in this area.

There have been various studies on radionuclides in coals, the bottom line of which seems to be that the levels are fairly trivial, but again, work continues. If the body of research finally indicates that these are important environmental problems, environmentalists and legislators will surely initiate appropriate legislation to control them.

COMMENT

Some of us would like to invest in cogeneration and other conservation methods, in more benign processes, while the problems inherent in, for instance, fluidized bed combustion are resolved. We would like to see the environmental problems solved beforehand rather than retroactively. We want benign energy sources that support our traditional society and patterns.

RESPONSE: Mr. Princiotta

The amount of electricity produced can be increased in three major ways—by nuclear power plants, coal-fired power plants, and combustion of oil and gas. Those are the three viable near-term options.

QUESTION

In sodium scrubbing, dilute solutions of sodium metabisulfite are being well-injected. These bisulfite solutions contain minute quantities of benadium, as well as particulate matter and copper. What is to be done with these well-injected sodium metabisulfite solutions? Do you plan to issue any guidelines toward the discontinuance of well-injecting?

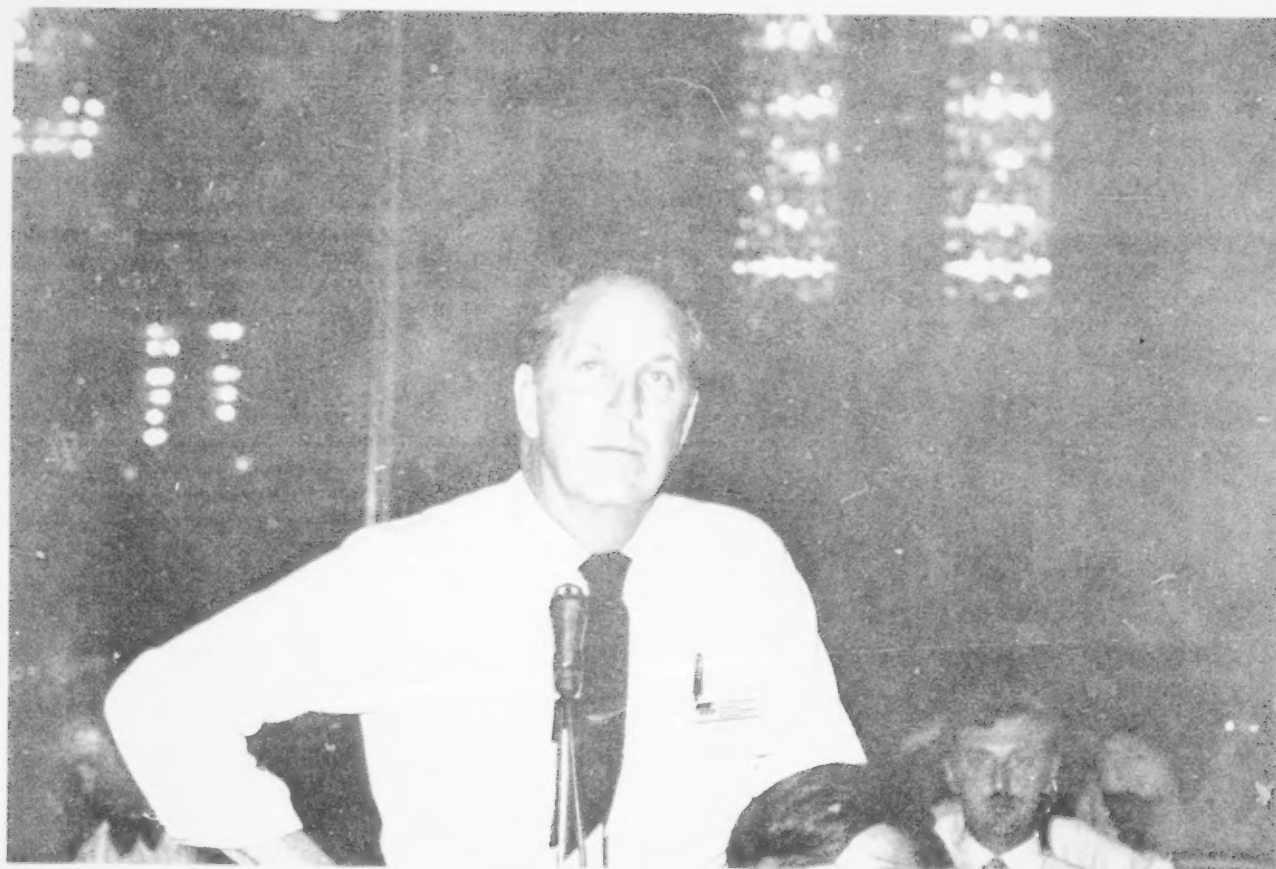
RESPONSE: Mr. Jones

In general, we tend in our program to concentrate on the big problems. Should sodium scrubbing become a major approach to control, the disposal or treatment of those particular streams would become a part of our program, because it would be of concern to the regulatory part of the agency.

COMMENT

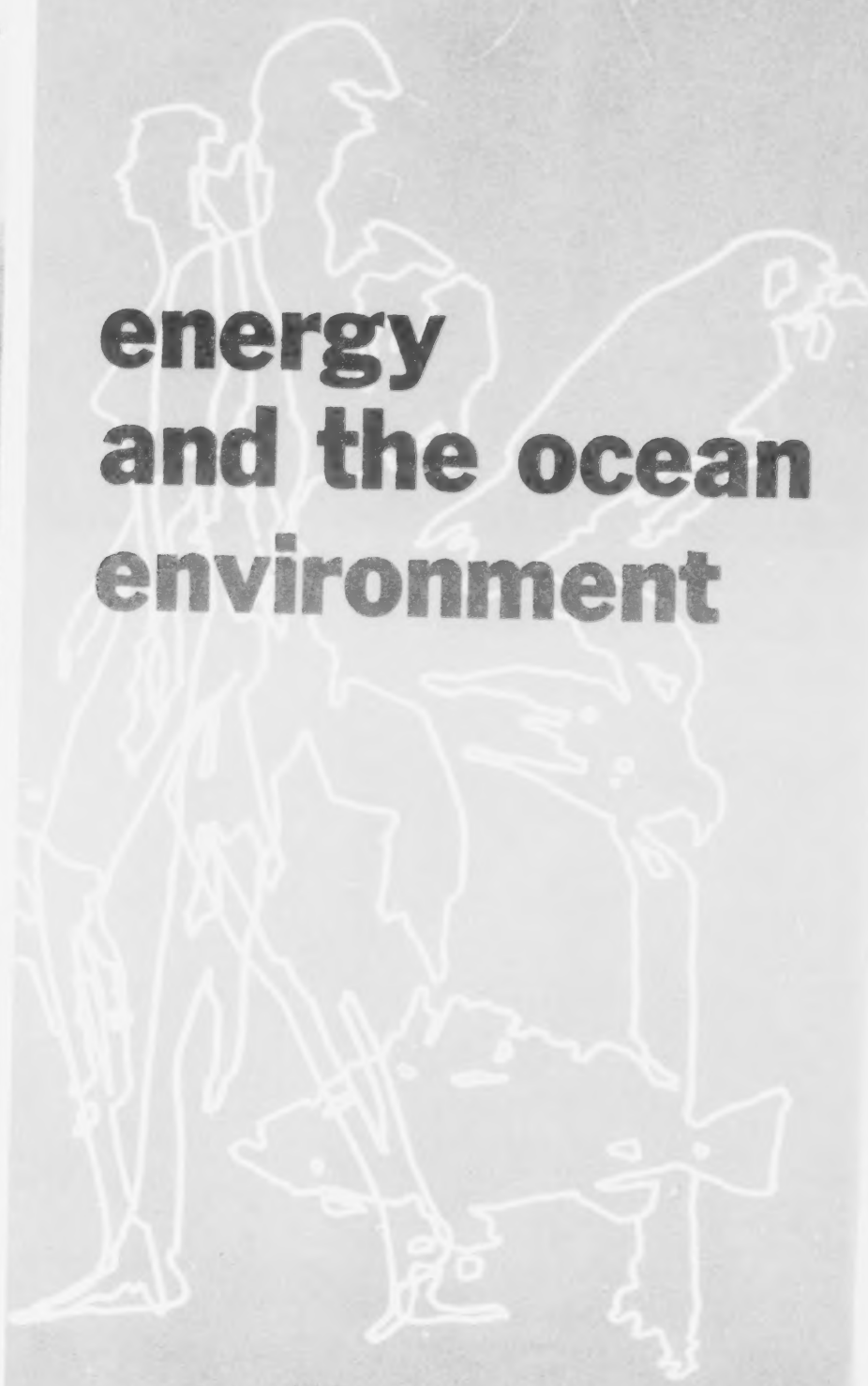
There have been some negative thoughts expressed concerning the willingness of the government to listen to comments about achieving a benign environment. Washington appears to have a large number of people working hard to achieve such an environment. However, what sometimes appears initially to be benign may not be

so benign or risk free. Solar energy, for example, actually utilizes a lot of glass and metal, both of which are manufactured commodities requiring plants that are apt to cause environmental problems. Everyone, on both sides of the fence, should try not to feel so defensive. Those working to achieve adequate energy supplies ought not to look at environmentalists negatively, nor should the environmentalists view the energy-minded faction as a different breed of cat. We are all in this together and should be listening and cooperating.



session 4

energy and the ocean environment



THE AMOCO CADIZ OIL SPILL

Wilmot N. Hess, Ph.D.
Environmental Research Laboratories
National Oceanic and Atmospheric Administration

U.S. ASSISTANCE

The AMOCO CADIZ oil spill produced the greatest impact on the environment of any oil spill up to that time. The spill occurred on March 16, 1978, 2 miles off the coast of Brittany in the northwest corner of France, near the little fishing village of Portsall (Figure 1). This ship riddled itself of its 220,000-ton load of light crude oil in about 2 weeks.

A United States team consisting of biologists from EPA, physical and chemical oceanographers from NOAA, representatives of the Coast Guard, and university members were on the scene within about 3 days. The team had previous experience with the ARGO MERCHANT spill. Ascertaining that the French would welcome assistance, they went in to help in such tasks as sampling oil in awkward situations, measuring the extent of the oil slick, and mapping oil on the beaches.

The AMOCO CADIZ broke in half on the second day and into three parts later on (Figure 2). Oil from the wreck spread rapidly, driven eastward along the shore by the wind, but very little got as far east as the Gulf of St. Malo or the Channel Islands. The major area impacted was along the coast of Brittany from Le Conquet to the Sillon de Talbert where winds from the west and northwest drove the oil directly onto the shore. Two estuaries directly faced the oil, and the northward-extending beaches about 100 kilometers to the east of the site of the spill received especially large amounts.

MOUSSE

From the air, Portsall looked charming and pleasantly idyllic but at close range not quite so idyllic. The area around the village and for a considerable distance to the east had large deposits of mousse—the emulsion that results when crude oil interacts

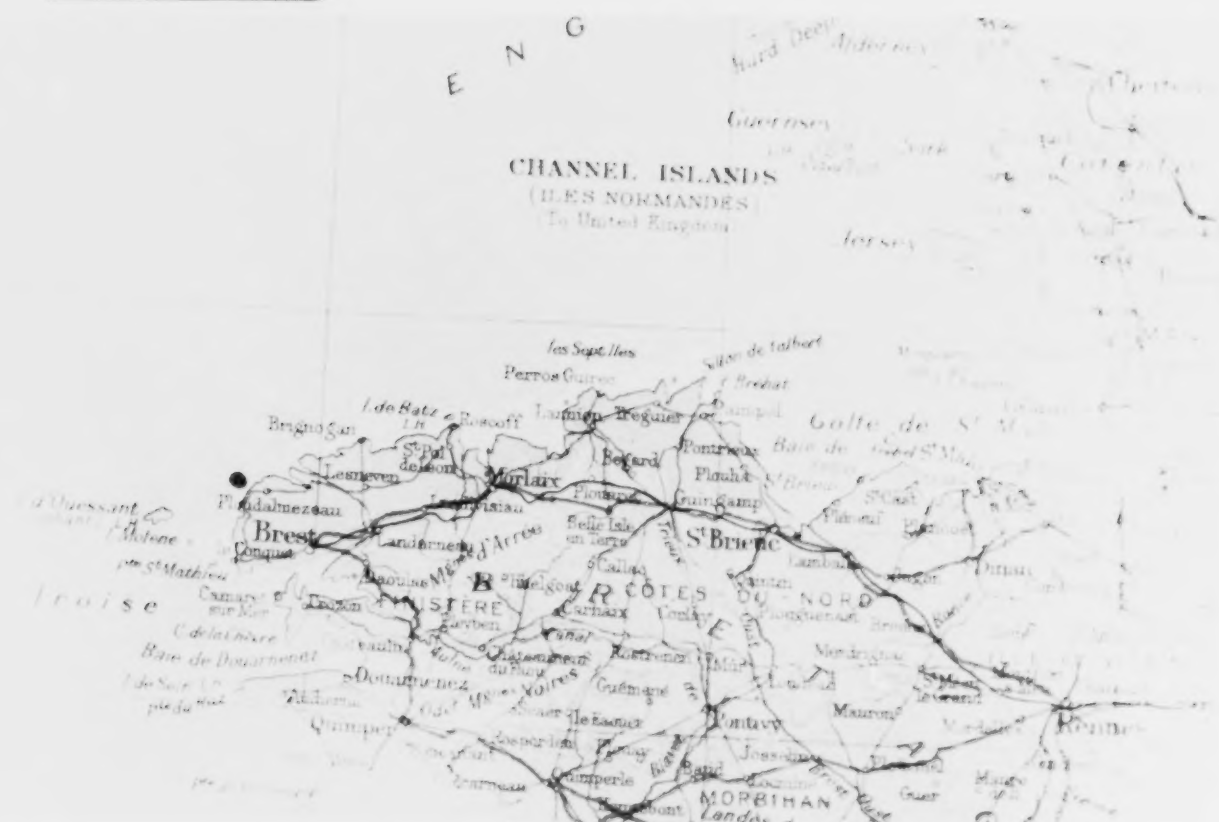


FIGURE 1—Map of Brittany coast of France with wreck site marked by dot



FIGURE 2—Photo of AMOCO CADIZ on March 28, 1978

PLASTERED AGAINST THE BEACHES

A TOWN HEAVILY IMPACTED

with water (Figure 3). Mousse is typically two parts water to one part oil. It is the color and consistency of chocolate pudding and is extremely difficult to clean up.

In the first 2 weeks, oil impacted about 140 kilometers of coast. Our team selected certain beaches on which to measure the effects, persistence, and amount of oil. It did not accumulate uniformly throughout the region, but in selected areas. It was driven by the wind into corners and plastered against westward-facing beaches. Eastward-facing beaches were almost unaffected for the first 3 or 4 weeks. After a wind shift, the oil got on but in lesser amounts and with less damage because about 40 percent of light crude oil is made up of volatile materials that dissipate into the air in a matter of days. This volatile component contains many of the more toxic elements, so that after about a week the material becomes more benign.

The town of Roscoff was also heavily impacted (Figure 4). The wind-driven oil butted up against a jetty and puddled into some areas of the harbor. It extended past the jetty and around a point, yet had little impact on the eastward-facing beach for some period of time. Of about 30 standard sampling beaches, 2 were located in the Roscoff region.



FIGURE 3—Photo of heavily oiled beach at Portsall



FIGURE 4—Photo of harbor at Roscoff, showing heavy oiling especially in eastern corner where the wind drove the oil

Oil does not necessarily stay on beaches for long periods of time (Figure 5). Underground water flowing out through a beach, for example, tends to cleanse the beach. For the first 10 days or so, oil is mobile. At high tide it gets deposited and, as the tide backs off, a reasonable amount remains on the beach. This oil, however, is fairly easy to clean up. After about 10 days or more, the oil becomes much more sticky. It adheres to sediments and is not easily washed off.

SELF-CLEANSING AREAS

In areas of high-energy active waves against a headland, oil is held off the beach somewhat. Reflecting waves prevent it from accumulating directly on rocks. These areas are essentially self-cleansing, and therefore no action was taken by the cleanup troops to get rid of the oil. Regions can be classified according to their vulnerability to impact. These promptly self-cleansing areas have the lowest vulnerability.

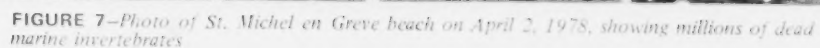
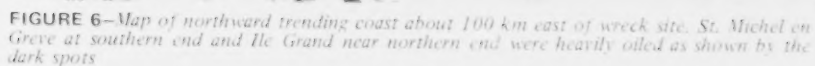
The characteristics of beaches change from day to day, depending on factors such as the direction and strength of the wind and the sand deposited or eroded. Oil under the sand on one day may be washed out on the next as a result of erosion. Therefore, the team from the University of South Carolina went down the beaches about every 3 days, drawing an elevation of the beach, characterizing the beach for oil content, and, where necessary, digging holes to measure buried oil. Done regularly along several transects for each of about 40 beaches and irregularly for another 100 beaches, this produced a good record of where the oil was, what its character was, and how much of it stayed there or went elsewhere eventually.



FIGURE 5—Photo of oiled beach where the ocean has cleaned the lower portion of the beach

PECULIAR MORTALITY DELAY

About 100 kilometers to the east of the spill site, a large amount of oil puddled against the northward-facing beach at St. Michel en Greve (Figure 6). This region was heavily oiled about 10 days after the wreck, causing extensive mortality of benthic fauna. Oil arrived at the beach on March 22, yet the mortality was not observed until about 10 days later. I walked that beach on April 2 and found up to 30 million dead animals along a stretch of about 4 miles (Figure 7). There were shells of clams, sea urchins, and cockles (Figure 8). Two days before my walk, however, a team had walked the same beach and had seen hardly any dead animals. Is there a delay built into this kind of process? Most of the creatures found dead on the beach were subtidal as opposed to intertidal and live below the tideline inside the sediments. It may be



that the animals started dying when the spill hit and, for reasons we do not understand, suddenly washed up on the beach 10 days later. It is also possible that a physical process not clear to us was operating. Chemists suggest that toxicity may change dramatically when oil is exposed to light. The first week after the wreck the weather was very bad and a continuous cloud cover prevented photooxidation. About April 1, light came through and photooxidizing compound changes were observed in chemical traces of oil samples. Whether the changes were great enough to influence the toxicity substantially is not clear, but this cannot be discounted as a possible explanation for the peculiar mortality delay.

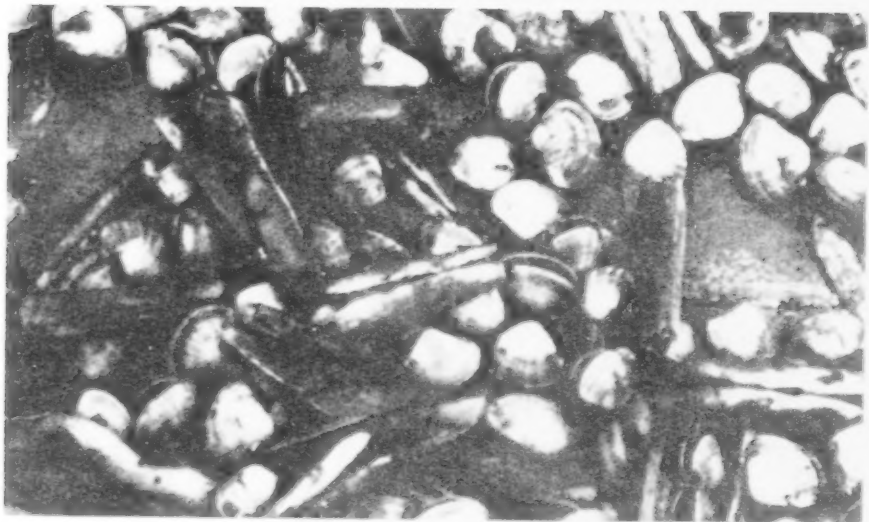


FIGURE 8—Closeup photo of St. Michel en Greve beach on April 2, 1978, showing dead razor clams and cockles and sea urchins (scale is 15 cm long)

FAUNA LOSS

In the Ile Grande marsh to the north (Figure 6), but still on the west-facing beach, oil puddled into the salt marsh. When oil arrived on March 22, about 10,000 tons puddled into the 100-acre marsh during the first day, creating a mousse on the marsh 10 or 20 centimeters thick (Figure 9). Ten centimeters of mousse was enough to smother most of the organisms there, and the number of fauna lost was very high. Almost all creatures living in the impacted area of the marsh were destroyed. There is, however, a bridge at Ile Grande marsh, and as soon as the oil arrived the area under the bridge was closed off; thus one side of the marsh was left essentially untouched.



FIGURE 9—Aerial photo of Ile Grand salt marsh in early April 1978. This roughly 100-acre marsh has roughly 10,000 tons of mousse deposited on it.



FIGURE 10—Photo of mousse pool in Ile Grand salt marsh on April 2, 1978, showing dead worms and "bowls of spaghetti" which were bunches of dead worms.

Some animals survived right through the spill. The marine lugworm, *Arenicola*, did well in St. Michel, although other marine worms were having lots of difficulty. About 10 days after the spill in the Ile Grande marsh, clumps of dead worms, polychaetes, were discovered in pools (Figure 10). Apparently they were forced out of the ground by the oil and tried to find the last bit of fresh water. Water tends to puddle in the marsh, and the worms collected in spaghetti-like masses in the pools. On digging in the marsh, we found the kill of polychaetes to be almost total. Sea gulls in the area, however, were eating the meat of the dead razor clams and having a grand time. Lethality and mortality are sometimes relative terms.

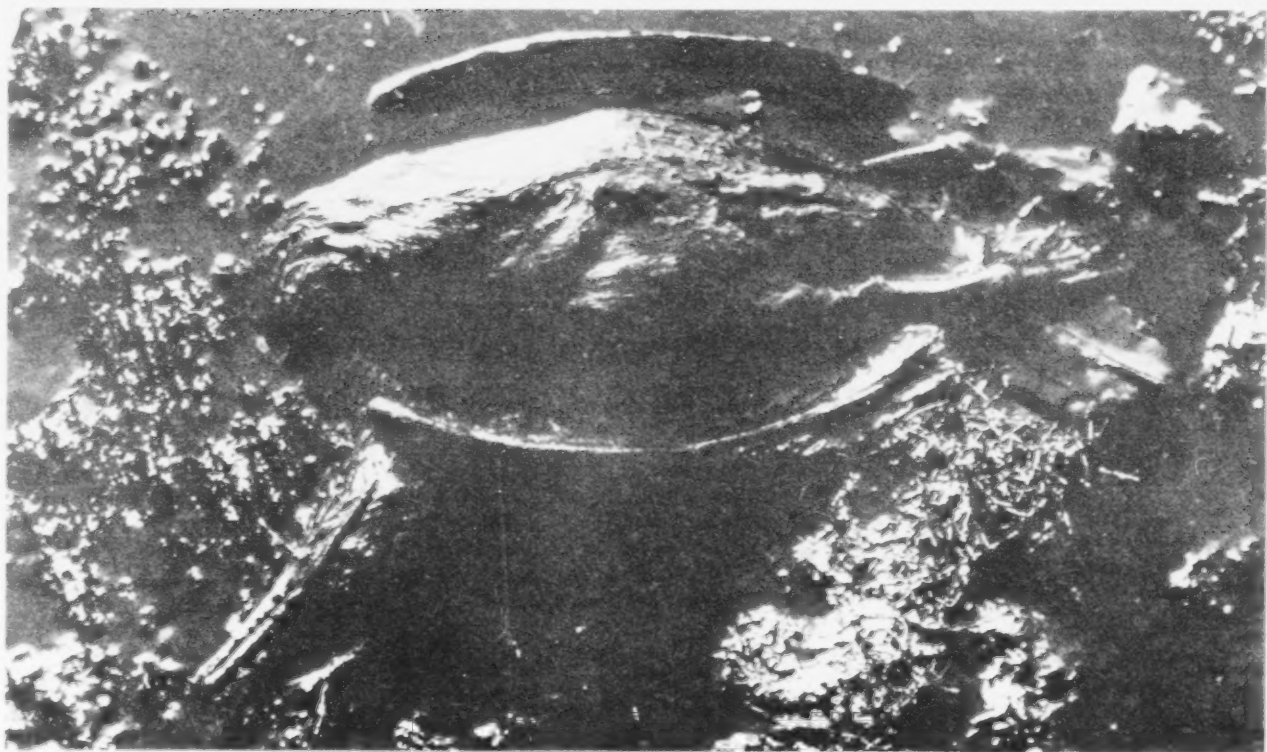


FIGURE 11—Photo of dead cormorant at Ile Grand, April 2, 1978

DEAD BIRDS

Although our team did not see a great many dead birds, the loss caused by the spill is probably 10,000 to 20,000 (Figure 11). Dead birds were collected mainly by bird hospitals in the area. The estimate is based on the collection of approximately 4,000 birds and the inefficiency of the collection process. The birds were primarily auks, puffins, guillemots and razor bills, species that spend much of their time in the water and are susceptible therefore to damage from oil in that water. The puffins were especially susceptible during this period because they were molting and therefore spending weeks in the oiled water. Approximately 700 puffins were found dead. The southernmost population of puffins in Europe was on Seven Islands (Les Sept Iles) off the Roscoff coast. That population has been decimated, perhaps completely lost. It should be noted that this population was also hurt badly at the time of the TORY CANYON spill.

There was not an especially good or well-tested plan for handling the cleanup, so the process took time to get organized. The French, however, did a very good job of getting people and equipment out. The cleanup force was made up of approximately 6,000 army troops, a large number of civilian volunteers, and a very large number of local residents who were interested in getting the Portsall beaches and hotels cleaned up for the summer tourist season. In Portsall harbor, where oil tended to puddle, they put skimmers in place and pumped the mousse directly into vacuum trucks.

INEFFECTIVE BOOMS

The booms that were used were ineffective (Figure 12). There were too few of them and they were improperly positioned so that oil came at right angles directly against the boom. In such situations the boom fails if there is more than a half-knot current and the oil goes underneath. To be effective, booms have to be set at an angle and must be continually maintained.

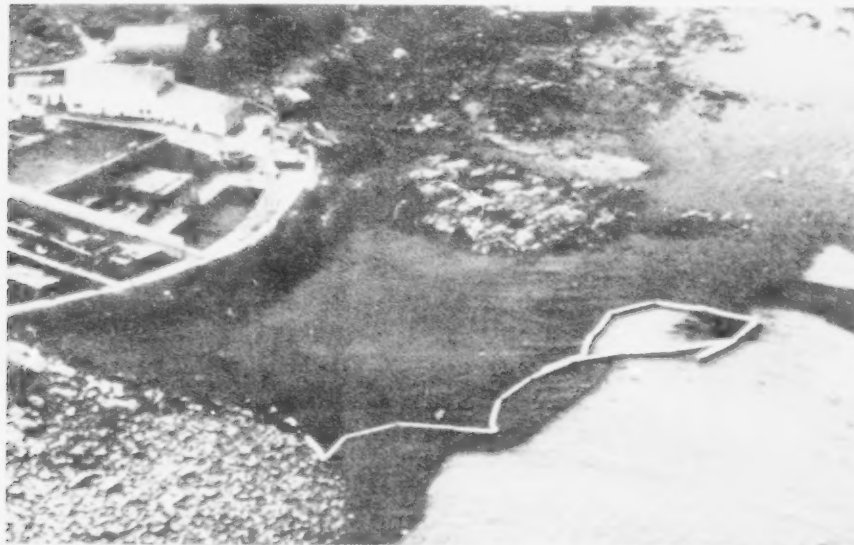


FIGURE 12—Aerial photo of beach at Roscoff, showing boom used to try to keep oil away from the lobster pound (circular structure in the foreground)

EFFECTS OF DETERGENTS

The major part of the cleanup was done by hand. Walls had to be washed repeatedly as new batches of oil came onshore (Figure 13). Although the French policy was that detergents would be used only offshore at the greater than 50-meter depth contour 3 to 4 miles out, in actuality detergents were used both onshore and offshore. In the main the detergents that were employed were much less toxic than those used at the TORY CANYON spill, and there is no identifiable loss from detergents in this spill.

The beach at Portsall was oiled every day for weeks. The cleanup crew pushed the oil around, collected it in whatever containers were at hand, and removed it from the beaches. The material was loaded into fertilizer carrier trucks, moved to temporary storage pits above the dunes and from there to large carriers that transported it to refineries or ships for ultimate disposal (Figure 3).



FIGURE 13—Photo showing seawall being washed with high pressure water to cleanse off the oil

FUTURE HEALTH PROBLEMS

We have been worried for some time about possible future health problems associated with the cleanup of spills. As I stated earlier, a great many volatiles come from oil and tend to be toxic. The people who worked 10 hours a day in the water handling oil got a fairly good dose of the volatiles, and, as a precautionary measure, blood samples and other samples are being taken.

In June, 3 months after the spill, the Portsall beaches were essentially clean and being used for swimming and fishing (Figure 14). Those who ate the fish reported that it was good. A rich crop of green seaweed was growing at St. Michel and there was a good mussel population along the edge of the beach. The Ile Grande marsh, on the other hand, was not in good shape. The French Government had decided that the best way to get rid of the oil in the marsh was to bulldoze the marsh cover, which in essence destroyed it. Our team considered this a mistake.

COMPLETE HISTORY SOUGHT

NOAA is now running a research program funded with \$2 million by the Amoco Transport Company that involves 10 teams of investigators from the United States and 10 from France. The teams continue to watch the processes of regeneration, rejuvenation, replenishment, and restoration of populations. There is particular interest in the restoration of the marsh which is being replanted according to schemes developed by the Corps of Engineers for stabilizing dredge spoil islands. Monitoring the marsh and other seriously damaged areas over the next 2 years, coupled with good coverage of the wreck and good biological knowledge about the area, will give us a complete history of this spill for a comprehensive idea of the total cost to the environment. The total biological damage appears to be considerably less than originally estimated.



FIGURE 14—Photo of Portsall beach in June with wreck in background. The beach is now clean (only dark patches are seaweed). This beach was very heavily oiled in March and April (see Figure 3)



Norman L. Richards, Ph.D.

EFFECTS OF CHEMICALS USED IN OIL AND GAS WELL-DRILLING OPERATIONS IN AQUATIC ENVIRONMENTS

Norman L. Richards, Ph.D.
Environmental Research Laboratory
U.S. Environmental Protection Agency

Intensified oil and gas exploration and development in the United States has resulted in more and deeper offshore wells. Additional lease tract sales are proposed by the Bureau of Land Management (Figure 1). This activity has heightened concern



FIGURE 1—Tracts proposed for oil and gas exploration and development

over the potential for environmental effects of drilling. The purpose of this paper is to (a) review the state-of-the-art in drilling fluids effects research, (b) summarize the interagency regulatory authorities that provide the present basis for offshore oil and gas decisionmaking, (c) state some examples of the limits of technical understanding of processes that could be impacted by offshore development, (d) propose a technical approach to the potential problem that could result in an improved basis for decision-making, and (e) review some recent achievements in drilling fluids-related research.

DRILLING FLUIDS

Recent environmental impact statements on oil and gas lease sales have devoted disproportionately little discussion to the environmental aspects of chemical use in well-drilling operations. This may reflect the fact that few studies have been done, and most are acute static toxicity tests that have little relevance to natural conditions where drilling mud discharges occur (1). Of those acute toxicity tests in the literature, few report adverse effects of drilling fluids or their components. Field observations have revealed a variety of marine life in the vicinity of drilling rigs (2). It is generally assumed that fluids either would have a limited local effect near the plume discharge point or would be dispersed rapidly and diluted in the field (1). Also, it has been assumed that many constituents of drilling fluids are sparingly soluble in seawater and, therefore, might be less biologically available to marine organisms. However, the assumptions have not been substantiated by peer-reviewed research publications.

Research on the environmental effects of drilling fluids and cuttings is further impeded by the chemical complexity of the mixtures of crude chemicals used to formulate mud; drilling fluid is a mixture of clay, water, and numerous chemical additives that is pumped downhole through the drillpipe and drillbit; mud cools the rapidly rotating bit, lubricates the drilling string as it turns in the wellbore, carries rock cuttings to the surface, and serves as a plaster to prevent the formation from crumbling or collapsing into the wellbore. Drilling mud also provides the weight or hydrostatic head to prevent extraneous fluids from entering the wellbore and to control downhole pressures. Chemical ingredients used to formulate mud can include everything from pH-control products, bactericides, calcium-removers, corrosion inhibitors, defoamers, emulsifiers, filtrate reducers, flocculants, foaming agents, lost circulation materials, lubricants, shale-control inhibitors, surface-active agents, thinners, dispersants, and viscosifiers to weighting agents (3). Analyses of potential effects of chemicals used in well-drilling operations must also take into account variations in mud and cutting composition related to type of substrate drilled, well depth, availability of mud components, temperatures generated, relative cost of components, operator experience, and so forth (2).

FATE AND EFFECTS RESEARCH

Consider the chemical complexity of drilling fluids, the diverse geographical conditions of areas being drilled, varying oceanographic conditions, the broad spectrum of aquatic organisms that could be exposed to drilling fluids during different seasons in different geographical locations, that very little is known about the basic biology of marine systems (4), and the resource-intensive nature of offshore research. It is not surprising that there is a dearth of peer-reviewed papers published in scientific journals on the effects of drilling fluids on marine organisms. Except for the present research that was sponsored through the Interagency Energy/Environment R&D Program and a few studies funded by Bureau of Land Management (BLM) (5, 6, 7, 8), most other studies in the United States were funded by oil companies and performed by contractors, often in response to federal government regulations (9). These studies were either (a) attached by the BLM to particular tracts offered for lease, (b) required as a drilling permit condition of approval by the U.S. Geological Survey (USGS), or (c) associated with Environmental Protection Agency National Pollutant Discharge Elimination System (NPDES) permits. Only a few copies of reports that result from these studies are printed; the scientific community does not have an opportunity to critique the conclusions before or after publication.

REGULATORY FRAMEWORK

The sequence of federal agency involvement in offshore oil and gas drilling operations has been described by Richards (10) and is illustrated in Figure 2. The process that allows private firms to purchase offshore leases involves a sequence of activities. The National Oceanic and Atmospheric Administration has authority to designate ocean areas with distinctive value as marine sanctuaries if presidential approval is received (11). Following a preliminary environmental impact assessment,

tracts are offered for sale by the BLM. A solicitation of nominations is accepted whereby industries can express interest in a tract, and environmental groups, states, and so forth can register objections (negative nominations). A draft environmental impact statement is then offered to federal agencies for comment. For example, the National Marine Fisheries Center of the U.S. Department of Commerce may comment on marine resources. The Geological Survey may comment on seismic activity; the Fish and Wildlife Service, on rare and endangered seabirds; state governments, on potential effects of development on resources or potential onshore impacts, and so on.

Following public hearings, the decision to lease for exploration and for ultimate development is rendered. Tracts that are leased for exploration may ultimately be developed for production. If this occurs, oil companies are required to comply with specific operating orders that are monitored and enforced by the U.S. Geological Survey.

EPA LEGISLATIVE AUTHORITY

An offshore operator must possess a valid and final NPDES permit from EPA. NPDES permits are issued by the EPA regional office that has jurisdiction over the drilling activity. The permit can stipulate a wide range of discharge requirements that depend on the Regional Administrator's assessment of the environmental damage

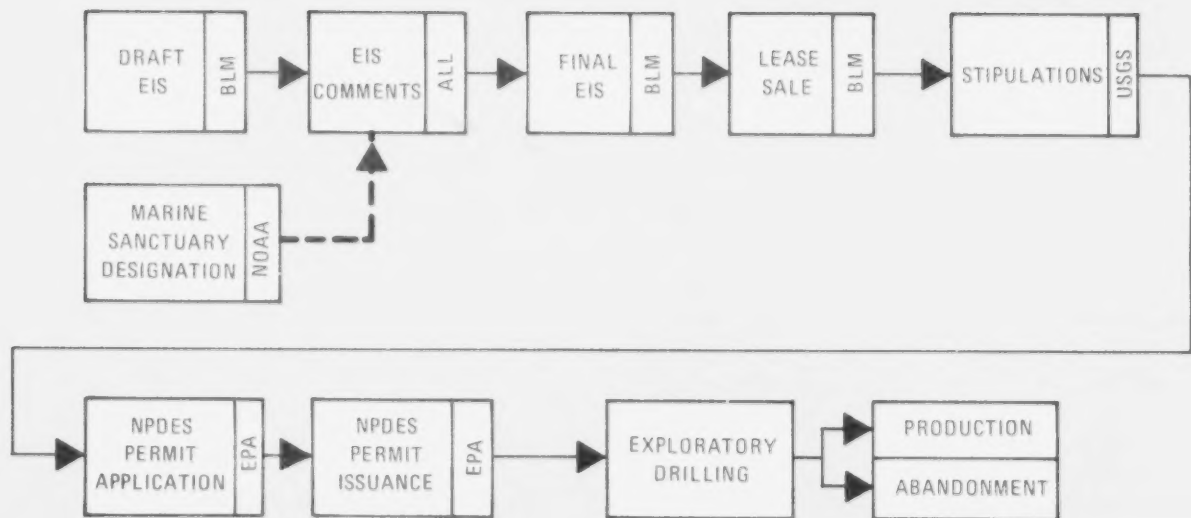


FIGURE 2—Sequence of federal agency involvement in offshore oil and gas drilling operations

likely to arise from the discharge. It is obvious that a high level of technical understanding of potential impacts is necessary to avoid over- or under-regulation. Table 1 illustrates the region-by-region diversity of areas, resources and additional concerns that are part of NPDES permit issuance.

HAZARD ASSESSMENT

Ongoing and future research is designed to assess the potential hazard to the aquatic environment and man from drilling practices and to evaluate mitigating options. Oil and gas drilling hazard assessment is based on (a) exposure assessment and (b) effects assessment. Figure 3 illustrates that potential damage to marine organisms may be predicted through knowledge of (a) environmental concentrations of xenobiotics that result from discharges and (b) the duration of exposure likely to be encountered by feral organisms under worst-case-exposure conditions. A hazard assessment based on knowledge of effects and environmental concentrations produces a better foundation to predict the environmental consequences of drilling. Mitigating options can be more easily selected from the spectrum of alternatives available to the region through permit issuance.

EXPOSURE ASSESSMENT

Figure 4 illustrates the stepped sequence of tasks performed in the effects assessment component of hazard assessment. It includes an iterative loop between field and laboratory research. The pyramid is based on a knowledge of chemicals used, but information is inadequate because (a) over a thousand trade-name products are used in drilling fluid formulation (12), (b) many components are known only by generic name, not by chemical composition, (c) most operators are unwilling to release drilling mud composition information, and (d) no drilling fluid plume and cutting studies have been published in scientific journals.

EPA exposure and effects assessment research needs to be closely coordinated in order to arrive at a hazard assessment with environmentally realistic concentrations.

TABLE 1

Special concerns: oil and gas development

EPA Region/Area	Representative Areas	Resources	Other Concerns
I N. Atlantic	Georges Bank	Commerical Fishery	
II Mid-Atlantic	Baltimore Canyon	Commercial Fishery	Slumping
IV S. Atlantic E. Gulf of Mexico	Blake Plateau Florida Middlegrounds	Commercial Fishery Coral Reefs	
V Great Lakes	Lake Erie	Drinking Water Commerical Fishery	Ice Salinity Eutrophication
VI Gulf of Mexico (Central & West)	Flower Garden Banks Gulf Coast	Coral Reefs Commercial Fishery	
IX California	Santa Barbara Channel Tanner Bank	Marine Mammals Commerical Fishery Coral Reefs	Seismicity
X Pacific N.W. & Alaska	Beaufort Sea	Commercial Fishery Marine Mammals	Ice Weather Assimilative Capacity Seismicity

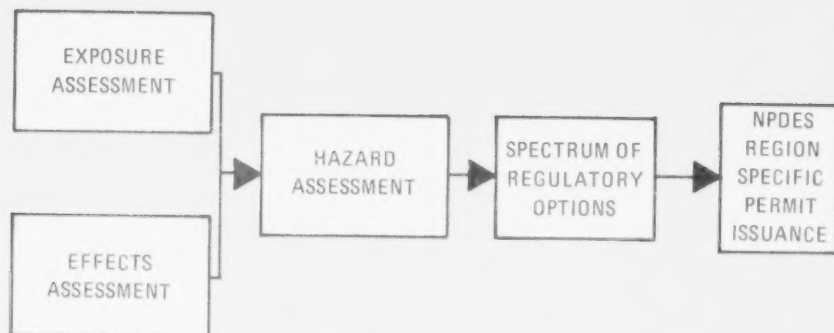


FIGURE 3—Environmental considerations in drilling permit issuance

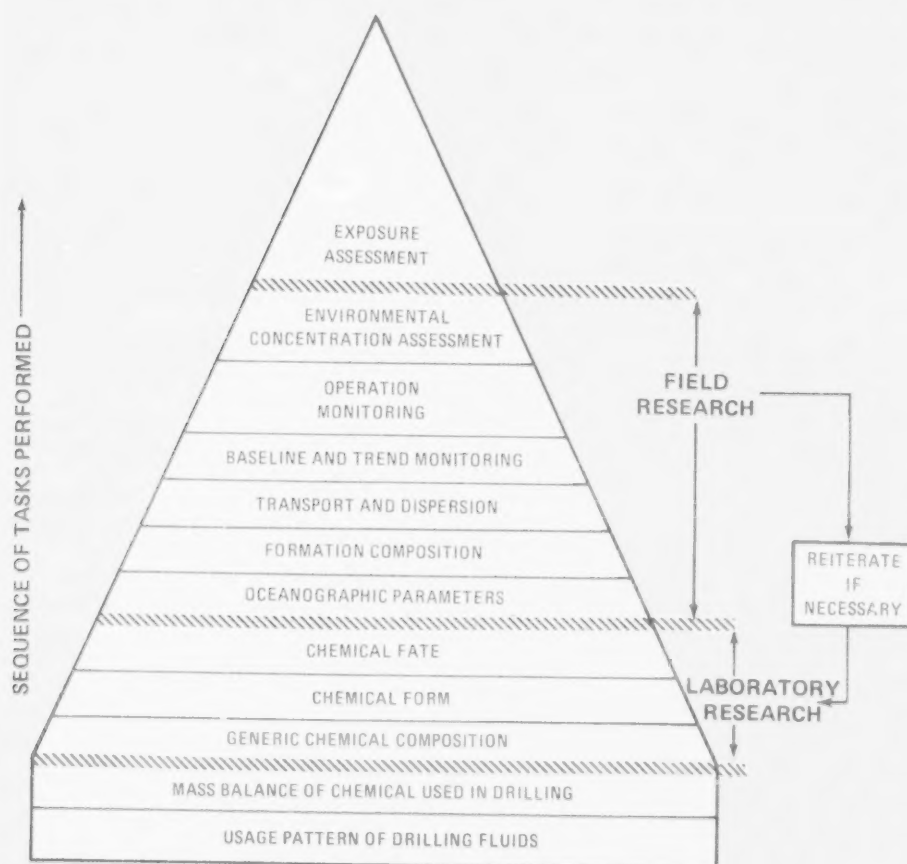


FIGURE 4—Stepped sequence of tasks leading to exposure assessment

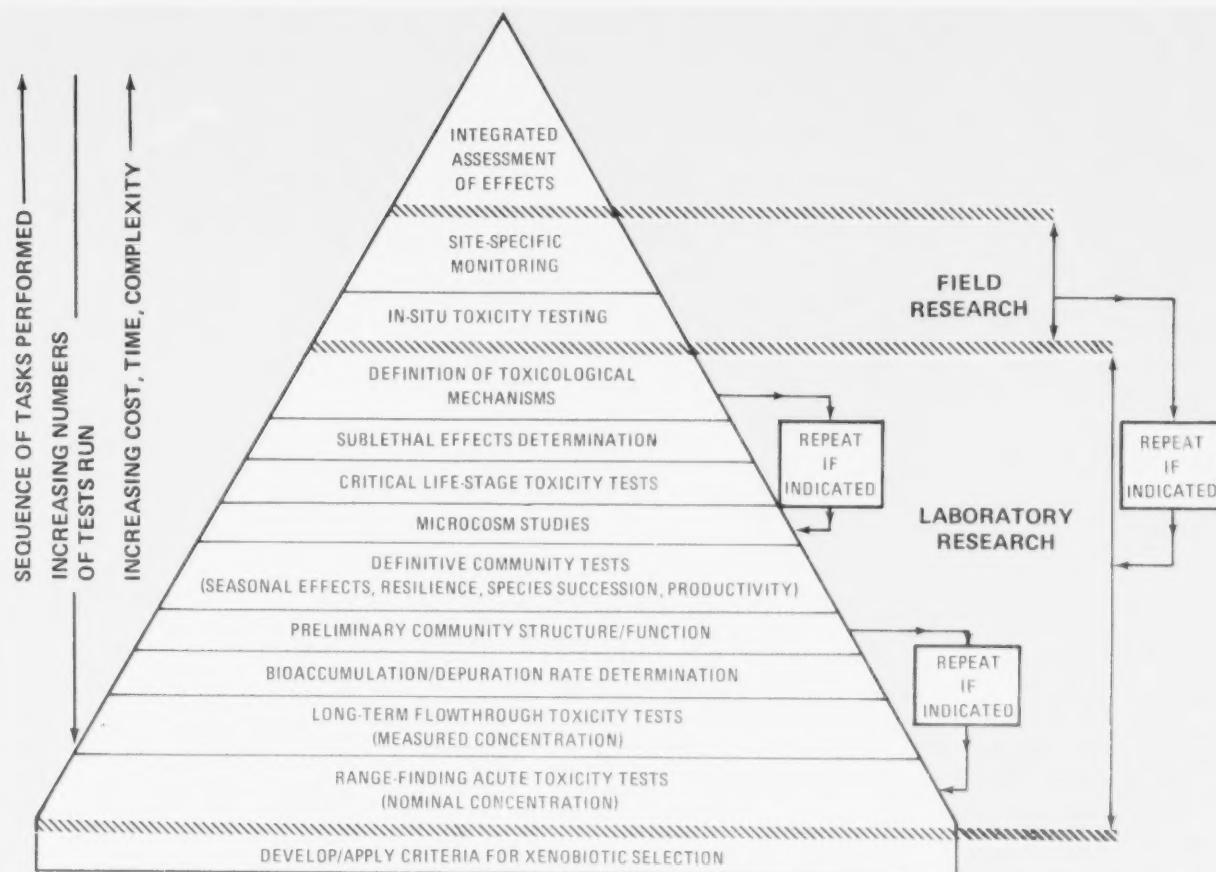


FIGURE 5—Stepped sequence of toxicity tests to assess xenobiotic effects on estuarine and offshore organisms

Figure 5 illustrates the conceptual basis for a stepped sequence of laboratory and field toxicity tests designed to assess drilling fluid effects on marine organisms and communities.

Preliminary screening of selected compounds is accomplished by acute static toxicity tests. Conducted with drilling fluids or their components, these range-finding tests aid in selecting toxicant concentrations for subsequent flowing seawater bioassays of each compound, component, or mixture of interest.

Flow-through toxicity test methods were selected for a higher tier of testing because they more nearly approximate *in situ* conditions. In contrast to static tests, metabolic products and excreta are removed, while oxygenated seawater and toxicant are continuously supplied. Data obtained from flow-through toxicity tests are generally preferable over static tests as the more precise measure of toxicity and bioaccumulation. A few compounds are selected from flow-through experiments for the next tier of testing: effect on composition and functions of estuarine communities.

XENOBIOTICS ANALYSIS

The effect of selected xenobiotics on colonization of planktonic larvae and microorganisms is analyzed by means of the apparatus and methods developed at the Gulf Breeze Laboratory (13). Seawater, with its natural components of plankton and microorganisms, is pumped to the laboratory and into the primary constant head box. Xenobiotics are continuously metered into the water after they are siphoned from a constant head box; the control apparatus receives the same flow of water. Water then flows from the secondary constant head box to each of 10 adjacent aquaria, that is 10 replicates for each treatment, including controls. At the end of an exposure period, microflora, macrofauna, and meiofauna are sampled. To determine the effect of the

xenobiotic after each treatment, numbers and species of microflora, meiofauna, and macrofauna in control and exposed aquaria are compared, and concentrations of xenobiotics in test water and sediment are determined. Samples of water from the constant head boxes are taken for xenobiotic analysis, and sediment cores from aquaria are taken from each apparatus at the end of the exposure. The tiered toxicity tests used in effects assessment have the following features:

- There is a continuing iteration between field observations and laboratory research.
- Relatively inexpensive and rapid rangefinding tests are used to minimize more resource-intensive tests.
- Community structure tests (14, 15, 16, 17, 18) can be used to detect both sensitive and resistant species for subsequent detailed testing.
- Effect and no-effect concentrations can be found expeditiously.
- The data can be used to estimate bioaccumulation rate, application factors, and maximum allowable toxicant concentration.

FATE AND TRANSPORT

Research tools for predicting the potential environmental fate and effects of drilling fluids are now becoming available. Figure 6 was composed from the plume data of Continental Shelf Associates (20) and community profile studies by Bright (21). Under the conditions studied, a near-surface discharge of drilling fluid did not disperse uniformly but concentrated above the thermocline (20). Adequate research has not been accomplished to determine the probability that a similar transport mechanism could ultimately cause exposure of coral reef communities in the Texas Flower Garden Banks. However, Figure 6 does illustrate that the potential for direct and/or indirect drilling fluid exposure via thermocline transport should be investigated under different hydrographic regimes. Shunting (discharging the drilling fluid to the nepheloid layer) has been proposed as an alternative to surface discharge (see broken line Figure 6). However, information on the transport and fate of shunted drilling fluids is inadequate for making an informed decision on the relative merit and hazard associated with shunting.

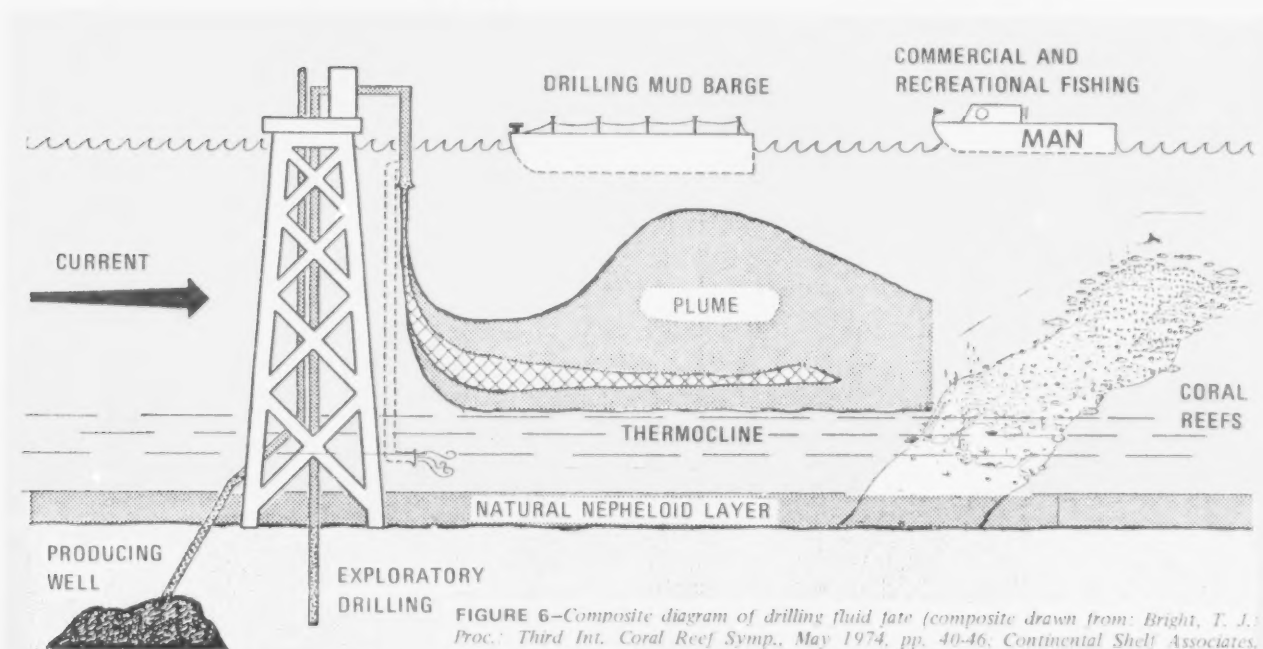


FIGURE 6—Composite diagram of drilling fluid fate (composite drawn from: Bright, T. J.: *Proc. Third Int. Coral Reef Symp.*, May 1974, pp. 40-46; Continental Shelf Associates, A. Report for American Natural Gas Production Company 1978; Richards, N. L.: *Proc. Env. Effects of Energy Related Activities on Marine/Estuarine Ecosystems*, 1977 EPA-600/7-77-111)

EFFECTS ON CORAL

Texas A&M University and EPA Environmental Research Laboratory at Gulf Breeze have a combined research program designed to determine the direct and indirect effects of drilling fluids on corals, coral communities, and coral reef processes. Current EPA experiments are run at a research laboratory located 12 miles offshore at Panama City, Florida. The purpose of this program is to determine concentrations of drilling fluids that affect the survival of corals. This research will be validated in offshore experiments.

Laboratory experiments on the effects of drilling fluid on benthic communities are part of the tiered toxicity tests diagrammed in Figure 7. Similar results of experiments with drilling fluids and their components on benthic estuarine organisms have been published (14, 15, 16, 17, 18, 19). Figure 7 illustrates the effects on aquaria containing sand initially covered with a 2 mm layer of drilling fluid on the composition of communities that developed from settled planktonic larvae in flowing seawater not containing sand. The average numbers of annelids, arthropods, and porifera were significantly less in treated aquaria than in untreated aquaria.

PERMITTING OPTIONS

EPA regional offices face a spectrum of regulatory options concerned with the discharge of drilling fluids into aquatic environments. Table 2 summarizes some of the options. Although completely adequate and timely data are not likely to be available now for NPDES permit issuance, regional offices must make the best possible decision from the limited data available. Ideally, both over- and under-regulation should be minimized through timely and scientifically defensible research. In this way, scientifically gained data on environmental concentrations and toxicological effects of drilling fluids may help eliminate unjustified concern about certain chemicals being used in drilling fluids. Similarly, modified operating procedures or drilling fluid ingredient substitution may help mitigate environmental effects that are observed in region-specific field- and laboratory-based research programs.

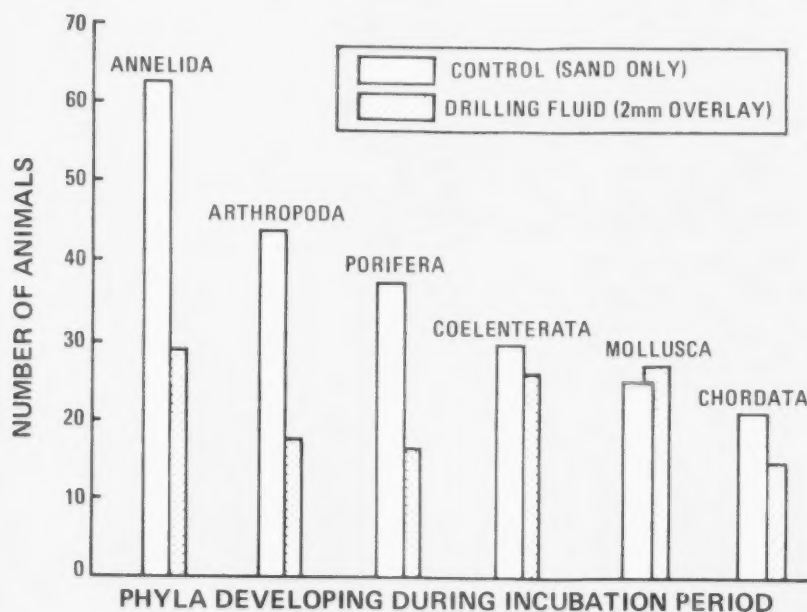


FIGURE 7—Effect of drilling fluid on development of aquarium community structure

TABLE 2

Spectrum of regulatory options for drilling fluids discharge

-
- Drilling prohibited
 - No-discharge permits
 - Barge wastes to remote location
 - Ocean disposal at designated dumpsites
 - Ocean disposal in abyss
 - Land disposal
 - Reprocess/recycle
 - Limited discharge permit
 - Barge portions of fluids/cuttings
 - Selective treatment of types of fluids
 - Black/gray/white list of components prior to drilling
 - Case-by-case permits
 - Geographical restrictions
 - Special resources
 - Rare/endangered species
 - Climactic restrictions
 - Season of year
 - Discharge, but monitor environmental effects/concentrations
 - Discharge rate stipulation
 - Up to preselected rate
 - Bulk discharge prohibition
 - Situation discharge (current, mix rate, etc.)
 - Shunt
 - To bottom
 - Below surface
 - Restrict/prohibit fishing
 - Unrestricted discharge
-

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questions & answers

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Holliston Conservation Committee

Dr. Margaret E. Hamilton
Delaware Chapter, National Audubon Society

A. M. Natkin
Exxon Corporation

Peter H. Debes
College of Environmental Science and
Forestry at Syracuse, NY

Richard Wood
Niagara Mohawk Power Corporation

David C. Clink
Automation Industries, Inc.

QUESTION

The plutonium levels in mussels in Plymouth, Massachusetts were mentioned. That site would be the Pilgrim I nuclear generator, Boston Edison, which operates that generator, as a public relations gesture, created a park at the water discharge area. The public is free to harvest mussels and fish, to picnic and enjoy assorted benefits of nuclear generation. As there is plutonium present in these mussels, would anyone care to comment on possible health hazards to the public?

RESPONSE: Dr. Donald Phelps (EPA)

The presence of transuranic radionuclides is not limited to the Pilgrim site, but appears to be part of a phenomenon of elevated levels. The degree to which that elevation makes them more or less a hazard to humans is a research question.

QUESTION

The Nova film, Black Tide, describes where the oil from the AMOCO CADIZ spill went. Estimates as to how much was actually dissolved in the water, how much was deposited on the beaches, carried away, and so forth were made in the film. At that time, 40,000 to 50,000 tons were still unaccounted for. Has anyone an idea where that amount of oil went?



RESPONSE: Dr. Wilmot N. Hess (NOAA)

Of the 220,000 tons released, about 80,000 tons evaporated in the first 10 days and 65,000 tons were deposited on the beaches. The rest of the oil was unaccounted for quantitatively because of the inability to sample widely enough to find out how much was in the sediments of subtidal regime or in the water column. Probably a large fraction of that unaccounted for 75,000 tons went into the water column and was widely dispersed, but there is no way to go back and reconstruct that. Later on, as cleanup progressed, much less oil was on the beaches, because of the action of the cleanup forces, but considerably more was found in subtidal sediments, especially in the bays of Morlaix and Lannion. At the end of the summer it was estimated that there were 40,000 tons of oil in or resting on the surface of the subtidal sediments. That oil is gradually going away, but there is still a considerable amount of oil in the estuaries. The next update on the status of the oil will take place in November 1979 at an international conference in Brest.

QUESTION

How long is it estimated to take the fishing and seafood industries to recover from the effects of the AMOCO CADIZ oil spill?

RESPONSE: Dr. Hess

The fishing industry is more or less back to normal now; the oyster culture industry is still in fairly bad shape. Last year, 9,000 tons of oysters in the bays of Morlaix and Lannion were destroyed because of tainting. Oysters ordinarily have about 60 ppm hydrocarbons. The oysters that were destroyed had a few hundred ppm. The French government decided it was not worth trying to depurate them, to move them to a clean area and let them regenerate, so they destroyed them. It is not clear how soon those oyster beds will be available for culture again. It is probably going to be another couple of years.

QUESTION

NOAA is doing a fine job following up on the oil spills that have taken place, making expert scientific advice available to the people trying to clean up the spills, and putting out reports of excellent quality. How effective might the use of dispersants have been in the AMOCO CADIZ spill had the French government decided to use them more widely?

RESPONSE: Dr. Hess

They probably would not have helped very much close in early on, because the oil came onto the beach in such large amounts and the dispersants would not have stopped that. But there were situations where dispersants probably could have been used to advantage farther away from the beach and somewhat later when there still were good-sized oil slicks. Dispersants probably could have been used there fairly efficiently.

The United States has not decided upon the proper posture on the use of dispersants in spills. A feeling that dispersants should not be used probably goes back to the time of the TORY CANYON spill when dispersants were quite toxic. They are not nearly as toxic now. Still, each situation must be considered carefully to determine that dispersants will be useful and helpful in dispersing the oil and letting nature take care of it. In some situations strong dispersants on beaches do more damage than the oil. I feel that dispersants should be used more widely than it is presently considered they should be in the United States.

QUESTION

Of the approximately 1,000 chemicals mentioned as currently used in drilling muds, how many have been specifically tested for toxicity or carcinogenicity, and what is EPA's policy about using them for drilling before it has data on these?

RESPONSE: Dr. Norman L. Richards (EPA)

The figure 1,000 was quoted from a summary of the generic names of chemicals that have been used. It is a summary published by the American Petroleum Institute. There are many redundant trade names, and it is very difficult to go from a generic name to a specific chemical name. The problem is further compounded by the fact that even when it is possible to go to a specific chemical name, the chemicals are often very crude mixtures. In fact, some may be only 60 percent of what the label indicates and the remainder may be an unknown mixture. When these mixtures of chemicals are pumped downhole, very complex chemical reactions can take place, ending up with even more compounds being formed. Furthermore, when individual components are tested separately they appear to give a very different effect than when they are tested in combination. Very few have been tested, and of those that have been tested, entirely appropriate organisms have been tested in order to extrapolate to offshore conditions.

There are no published studies on mutagenicity and carcinogenicity. Most of the information is available only in informal reports, and even those have very limited distribution. Federal agencies, for example, will require only three copies of a report to be prepared, so it takes a great deal of detective work to get even the informal reports. When you do get them, they have not been subjected to peer journal type review. As a result, some results may be questionable.

Because each of EPA's Regional Offices deals with problems unique to that office, there is no hard and fast national policy regarding the use of these chemicals. The Regional Office issues the NPDES permits. For example, a great deal of money has gone into investigating eutrophication problems in Lake Erie. There is local concern that putting concentrated chemicals back into the lake presents a potential problem that does not now exist in marine waters. The brine water produced could add chloride to the water, which in turn could

produce ecological consequences in Lake Erie. Our office is attempting to provide the unique research information required by each of the unique problems of the regions.

QUESTION

In view of the current concern over the potential presence of various toxic chemicals in fresh waters, has any thought been given to the possibility of an approach similar to Mussel Watch for fresh waters using freshwater species?

RESPONSE: Dr. Phelps

Although I am not aware of such an approach for freshwater at this time, the concept certainly is applicable and expandable. The basic ingredient is designating a suitable organism that has a ubiquitous distribution and does not move around a great deal.

QUESTION

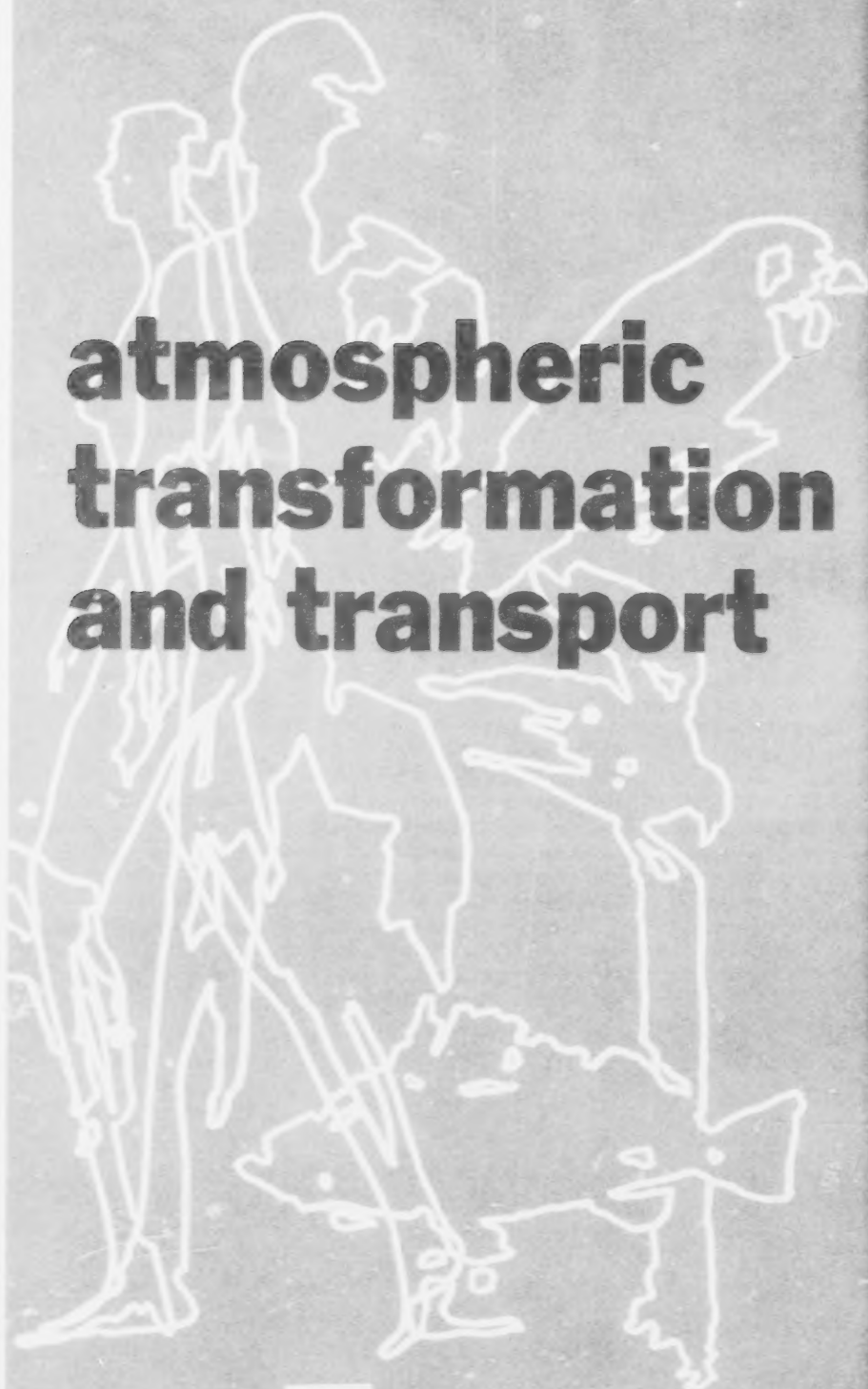
In view of the obvious catastrophic effects of oil incidents similar to the AMOCO CADIZ, what is the feasibility or practicability of using incendiary devices to prevent the oil from getting ashore by burning it in the ship?

RESPONSE: Dr. Hess

That has been done several times. It was tried at the TORY CANYON, but it did not work very well. It was tried in a spill on ice in Buzzards Bay a year ago, and it did work to a limited extent there. The problem is to get the oil puddled and wick it somehow, and to apply a high enough temperature to cause it to burn well. One of the problems is that if the slick is some distance away from the ship, it is generally thin enough so that it is very difficult to get the temperature up high enough to get it to burn. If the decision is made to burn the oil at the ship, the first thing that must be done is to open the ship. This was tried unsuccessfully at the AMOCO CADIZ. It was tried at the TORY CANYON with no different success. Looking at it logically, even if you do get the ship open and set the oil on fire, what have you really accomplished? You have burned material which might have evaporated anyway. You may have helped by doing that, but it is rather unlikely that you really will successfully burn most of the heavies in the crude.

session 5

atmospheric transformation and transport





Walter A. Lyons, Ph.D.

SATELLITE OBSERVATIONS OF PERSISTENT ELEVATED POLLUTION EPISODES (PEPE)

Walter A. Lyons, Ph.D.
MESOMET, Inc.

INTRODUCTION

A new way of visualizing natural phenomena often helps us crystallize our understanding of basic physical processes. The recently appreciated ability of conventional meteorological satellites to routinely detect massive areas of turbidity in the atmosphere produced by both natural and anthropogenic sources has shed new perspectives on the problem of long-range pollution transport. This paper summarizes some of the observations of major aerosol events in the atmosphere and suggests that routine detection and tracking of synoptic scale pollution episodes, along with quantitative measurements of their intensity are entirely feasible with existing spacecraft and data analysis systems.

LONG-RANGE TRANSPORT

Long-range transport of certain long-lived atmospheric pollutants was graphically demonstrated 3 decades ago by the tracking of nuclear bomb debris, in some cases, for several circuits of the globe. The Clean Air Act of 1967 and 1970, however, had an underlying assumption that the concentrations of various primary pollutants at some unspecified distance, but not too far downwind from the source, would become indistinguishable from the natural background because of dilution, wet and dry deposition, and perhaps chemical transformation. During the 1970's, we have gradually come to realize how chemical transformations also generate secondary pollutants in significant concentrations, which become of greater concern at distances typically greater than 100 km (White et al., 1976).

Photochemical oxidants were measured by Blumenthal et al (1974), being exported out of the Los Angeles Basin at the rate of 100 tons/hour. Lyons and Cole (1976) noted that high ozone values recorded in both urban and rural sections of Wisconsin were the combined results of local emissions, mesoscale transport, and synoptic transport, all comingled in a manner making it most difficult to separate the fraction resulting from each mechanism. Coffey and Stasiuk (1975), Wolff et al (1977), and Ott and Lyons (1977) were among many suggesting that ozone-laden air masses could easily travel hundreds or even thousands of kilometers over several days. Periods

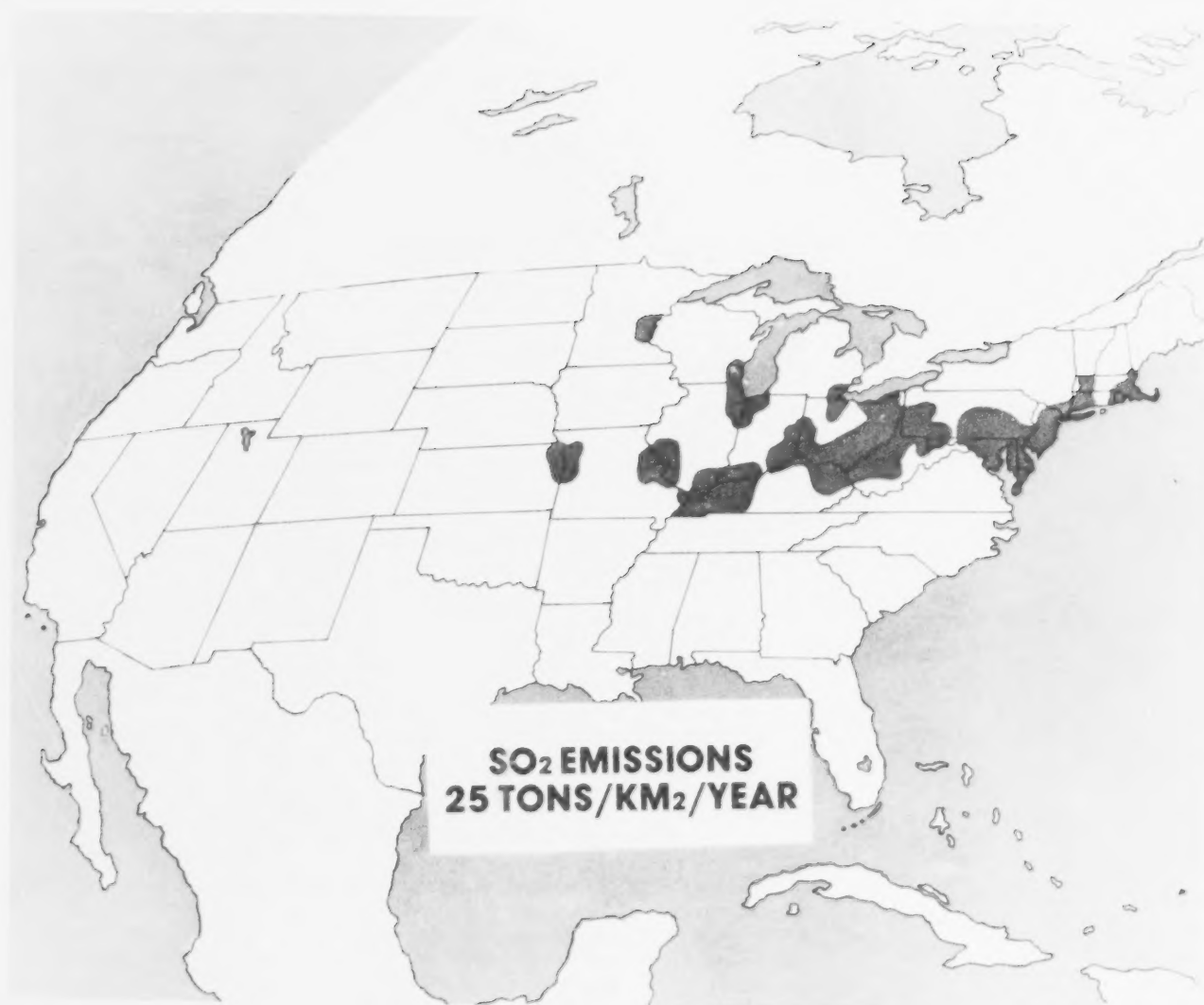


FIGURE 1—Map of regions where SO₂ emission density exceeds 25 tons per square kilometer per year

of elevated ozone in air masses undergoing long-range transport were also found associated with reduced visibility by Samson and Ragland, (1977). As research continued, such as project MISTT, it became clear that important secondary aerosol producing mechanisms were being found. The conversion of SO_2 gas into aerosols within individual power plant or urban plumes was documented by many, including White et al (1976). The progressive deterioration of regional visibility during summer appears correlated to the increased SO_2 emissions into the upper portion of the boundary layer by the greater use of coal, as well as higher stacks, (Husar, 1978).

SULFATE AEROSOLS

The prime contributor to widespread areas of turbidity appears to be the conversion of SO_2 gas to sulfate aerosols, with transformation rates somewhere around 1 to several percent per hour, according to Wilson et al. Figure 1 maps the region with the highest SO_2 emission densities in the United States. The contributions of the coal burning power plants, especially in the Ohio River Valley and surrounding areas, are significant. The isopleths of maximum recorded sulfate levels (Figure 2) show the pattern centered near the major source regions, but with values exceeding $20 \mu\text{g}/\text{m}^3$ possible almost anywhere in the eastern United States. It is in this area that our search for satellite images revealing large scale pollution episodes will be focused.

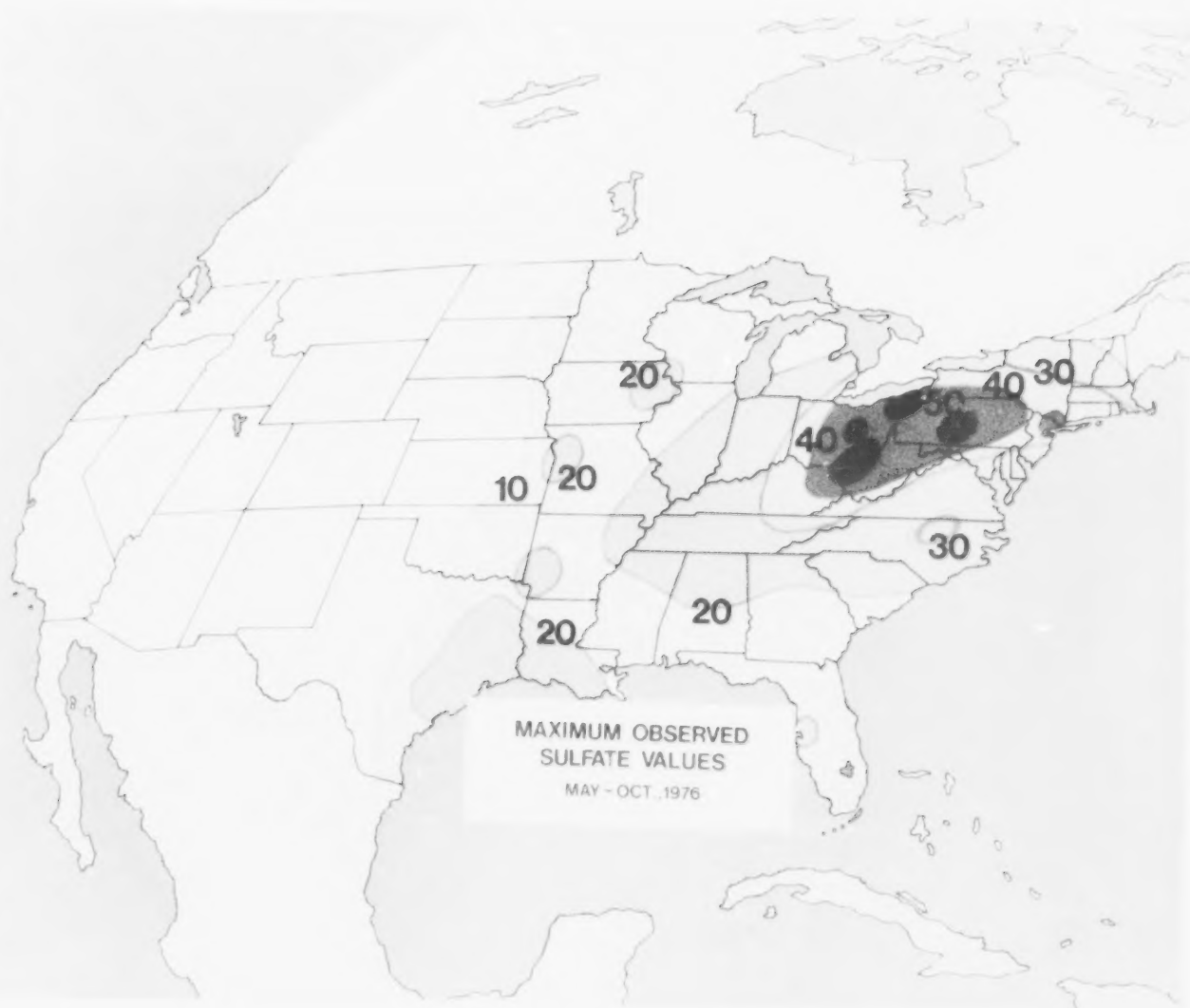


FIGURE 2—Plot of observed maximum sulfate values ($\mu\text{g}/\text{m}^3$) at NASN sites during May through October, 1976

GRAPHIC EXAMPLE

A graphic example of air mass pollution was provided by Samson (1979).^{*} Figure 3 is a view looking southeast from atop Whiteface Mountain in upstate New York at 1400 EDT, 26 August 1977. Back trajectory computations indicate the air to be of Canadian origin. Visual range appears to be well in excess of 20 n.mi. Figure 4 is a picture taken at exactly the same spot, looking in the same direction, at 1400 EDT, 28 August 1977—only 48 hours later. Trajectory analysis showed this air mass to have originated to the southwest of New York state. The visibility has dropped to several n.mi.

Reduced visibility or visual range is the result of the decreasing contrast of a distant object against a background caused by the scattering of light into the intervening volume of air. It is reasonable then to assume that measurements of visible wavelength radiation from an orbital platform would reveal both increased atmospheric brightness (turbidity) and reduced contrast of ground targets. The overall measurement would of course be a function of the aerosol constituency, size, and concentration, the albedo of the surface, the solar angle, the position of the spacecraft, and the sensitivity, resolution, and spectral response of the sensor.

SATELLITE DETECTION OF AEROSOLS

As early as 1971, Mohr noted anomalous areas of turbid air in ESSA satellite APT images over Europe and suggested the possibility of using conventional weather satellites to monitor regional air pollution events. In the same year, McLellan (1971) had some success in using the digital brightness readings from the geosynchronous ATS satellite to detect the smog buildup in the Los Angeles Basin by its enhanced upward light scatter.

^{*}Personal communication



FIGURE 3—View looking southeast from Whiteface Mountain, New York, 1800 GMT, 26 August 1977. A clean polar air mass dominated the area.

METEOROLOGICAL SATELLITES

Various satellite platforms are capable of detecting a wide variety of aerosol episodes in the atmosphere. Landsat images were analysed by Lyons and Pease (1973) and Lyons (1974), revealing point source smoke plumes traveling for more than 100 km over Lake Michigan. Lyons et al (1974) also noted apparent indications of high turbidity levels throughout entire air masses. Unfortunately the small areal and infrequent temporal coverage of Landsat makes synoptic monitoring impractical. The same could be said of 35 mm photography from manned spacecraft missions, although some individual scenes of note were described by Randerson (1968, 1978).

The operational meteorological satellite, while designed to detect bright, high contrast clouds, has shown itself suitable for mapping large scale areas of atmospheric dust, haze, and smoke. The SMS/GOES (Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite) series has been used for this research (Ensor, 1978). Two systems observe the United States from 36,000 km above the equator, one centered at 75° W, the second at 135° W longitude. Every 30 minutes, subpoint 4 km resolution infrared (10.5-12.5 μ m) scans of the earth are made from pole to pole. During daylight hours, visible images at 0.7 km subpoint resolution are obtained at the same interval. The visual infrared spin-scan radiometer (VISSR) responds to visible light in the 0.54 to 0.70 μ m band. Data are transmitted from the satellite at 8-bit resolution. The enormous data volume (4×10^{11} bits/day) is managed in many ways, but primarily by conversion to photographic form. However, special computer-based systems do allow investigations to access and manipulate the data quantitatively.



FIGURE 4—Same as Figure 3., but exactly 48 hours later, Visibility has dropped to several miles.

MAJOR AEROSOL EVENT

Figure 5 is an example of a major aerosol event in the atmosphere—a massive plume of smoke from the Hawaiian volcanic eruption of September 1977. On subsequent days, the plume drifted in a cohesive manner in the trade winds for many hundreds of miles (Cochran and Pyle, 1978). Shenk and Curran (1974) were among the first to note the cross-Atlantic transport of large clouds of Saharan dust. During June 1977 a dust cloud reached Cuba after having left the African coast less than 5 days before, all the while visible in the SMS/GOES visible imagery. During the U.S. drought of 1977, several major dust storms occurred in the central U.S. One such raged from 23 to 25 February 1977. On 24 February the satellite detected a plume of dust stretching from the Oklahoma Panhandle to Georgia (Figure 6). It was subsequently seen to spread over the Atlantic as far east as Bermuda. During the passage, local visibilities dropped as low as 1 to 3 miles (Purvis, 1977). Hi-vol aerosol measurements taken by the Texas Air Resources Board found 24-hour averages ranging from around $600 \mu\text{g}/\text{m}^3$ near Houston to as high as $2450 \mu\text{g}/\text{m}^3$ in northeast Texas.

AGRICULTURAL BURNING

An often overlooked source of man-made pollution is smoke from agricultural burning. As noted by Parmenter (1971), massive areas of slash burning in southern Mexico, Yucatan, and Guatemala during the late winter dry season generated massive smoke palls over much of the Gulf of Mexico. Figure 7 shows one of the many such incidents noted in recent years. These smoke-filled air masses frequently reach the southern U.S.

Smoke from giant forest fires in the western U.S. can routinely be monitored on SMS/GOES imagery as have massive smoke palls from Florida Everglades fires



FIGURE 5—SMS/GOES 1.0 km resolution visible image, showing plume of smoke from Hawaiian volcanic eruption drifting several hundred kilometers southwestward, at 0300 GMT, 16 September 1977.

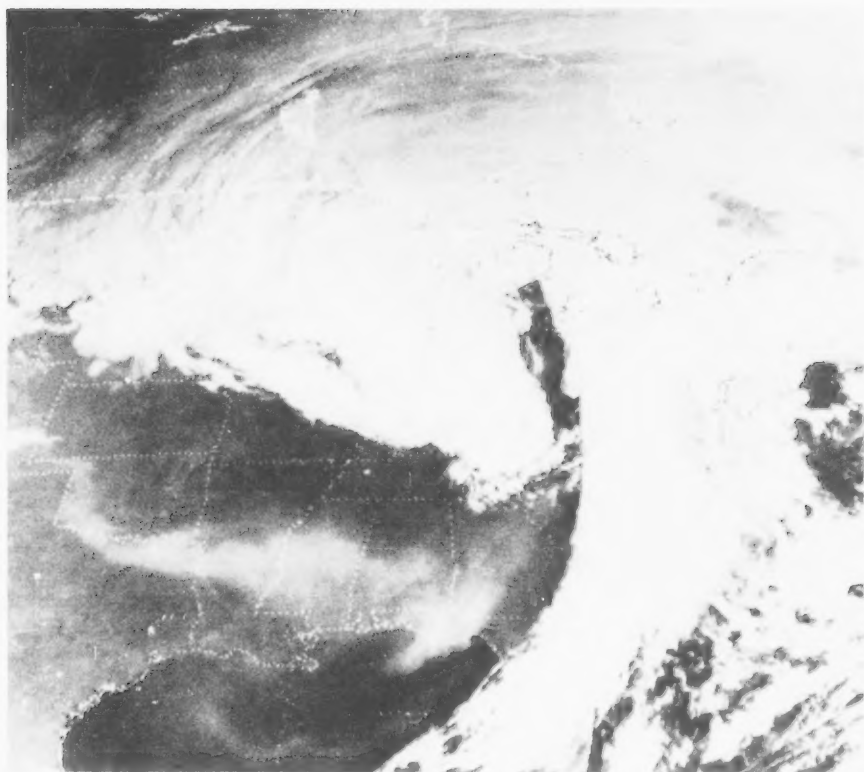


FIGURE 6—SMS/GOES 2.0 km resolution visible image, 1530 GMT, 25 February 1977, shows cloud of dust stretching from Oklahoma panhandle to Georgia. Dust cloud followed cold front many hundreds of miles into the Atlantic.



FIGURE 7—SMS/GOES 2.0 km resolution visible image, 1700 GMT, 30 April 1975, showing large area of smoke over Yucatan and the Western Gulf of Mexico, the result of widespread agricultural slash burning.

(Snyder et al, 1976). However, the plume of smoke from a small northern Minnesota forest fire, is shown in its seventh hour (Figure 8) after having been tracked at 30-minute intervals from its inception that morning.

MIDWEST HAZE

Lyons and Husar (1976) presented an SMS/GOES picture, showing a large area of haze covering the Midwest. Comparisons with other data showed the area to be associated with reduced visibility (6 n.mi. or less), high sulfate concentrations, and generally elevated ozone levels. The photograph showed a typical episode—on the scale of 1,000 km, lasting for several days to nearly 2 weeks, associated with a warm moist air mass that had significant injections of SO_2 from major source regions. That particular image first needed a certain degree of photographic darkroom enhancement to make the smog blob or hazy blob or elevated pollution episode clearly recognizable.



FIGURE 8—Blow up of SMS/GOES 1.0 km resolution visible image, 2200 GMT, 29 September 1976, showing plume of smoke from a small forest fire in northern Minnesota, having drifted about 100 km southeast after about 7 hours

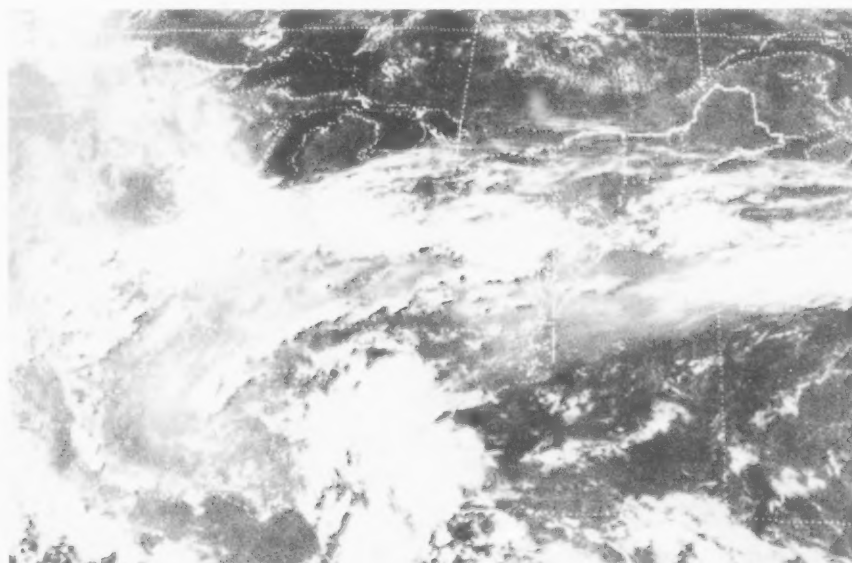


FIGURE 9—SMS/GOES image, 2.0 km resolution, 2200 GMT, 25 June 1975

The image described by Lyons and Husar was taken on 30 June 1975, the midpoint of an episode lasting from before 25 June until after 5 July. Figures 9, 10, and 11 show 1.0 n.mi. resolution images of the eastern U.S. on 25 and 29 June and 3 July 1975. The area of haze, while it did shift its position during this time frame, generally was more than 25% of the U.S. on any given day. During the end of the episode, around 3 July, when it was centered in the southeast, elevated ozone values in rural areas caused notable damage to eastern white pine forests (Hayes and Skelly, 1977).

SECONDARY POLLUTANTS

A persistent high pressure cell during this nearly 2-week long stagnation caused an accumulation of secondary pollutants from the lower Ohio River Valley, which were then transported as far as Louisiana and Minnesota. Trajectories produced by Brand Nieman at Teknekron, Inc. confirm this overall flow pattern by analysis of

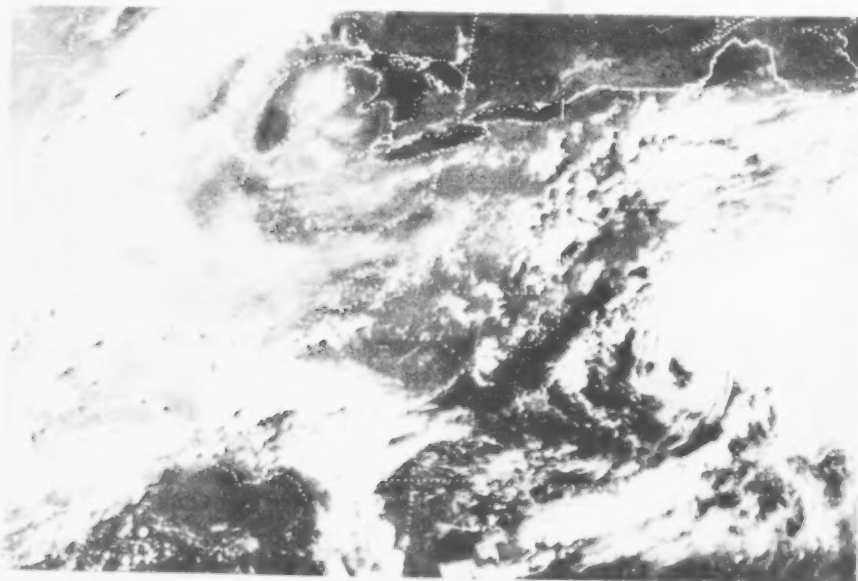


FIGURE 10—SMS/GOES image, 2.0 km resolution 2200 GMT, 26 June 1975

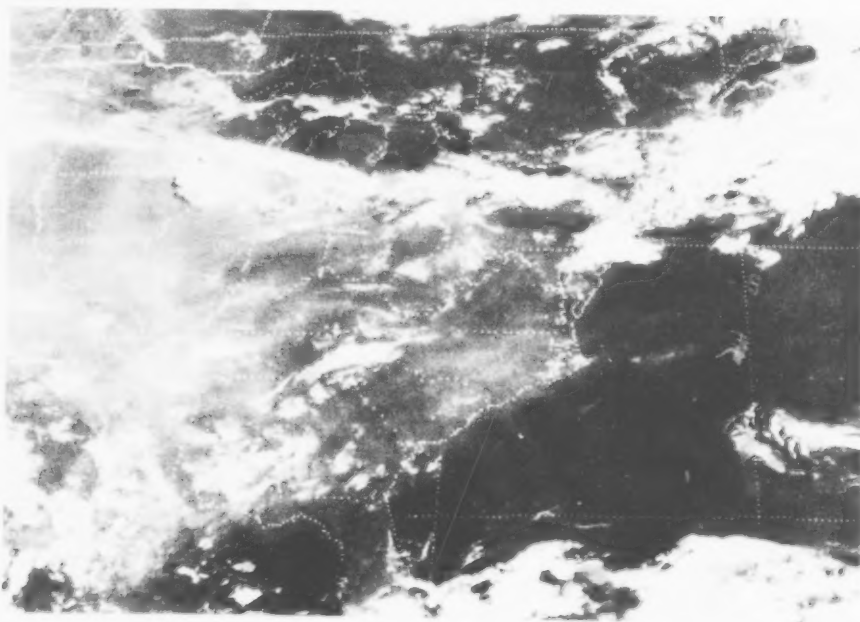


FIGURE 11—SMS/GOES image, 2.0 km resolution, 1400 GMT, 3 July 1975

150 and 600 m winds. Figure 12 summarizes some of the measurements made on 29-30 June 1975. The visibility contours show that noontime readings (6.4, 3, and 2.7 n.mi.) closely correlate to the haze area seen on the satellite image. Those ozone monitoring sites reporting 1-hour averages of 160 PPB or higher were located in or near the blob. Scattered sulfate measurements showed values as high as 80 $\mu\text{g}/\text{m}^3$ within the haze boundary, and generally 15 $\mu\text{g}/\text{m}^3$ or less outside.

During the period 27 June to 4 July, persistent southerly winds transported portions of this blob into Minnesota. Ozone monitors in rural areas of central Minnesota reported frequent readings in excess of 80 PPB and often above 120 PPB. This ozone was suspected of being capable of reducing yields of the state's soybean crop of more than 10% at the level and duration measured (Laurence et al, 1977).

HOLES IN THE BLOB

Of note in Figure 10, in addition to the widespread obscuration of ground features by haze in cloud-free areas, are pockets of reduced turbidity or holes in the blob. Film animation shows that these travel with the general low-level winds, and retain continuity for a day or more. There is considerable circumstantial evidence relating these to areas of wash out by prior thunderstorms. Knowledge of such regions from satellite images would greatly aid in analyzing surface and aircraft aerosol measurements. The volume of air undergoing significant wet removal can also be calculated from such convective footprints if correlated to radar data. A dynamic real-time data gathering system using color digital remote radar systems now available would allow for field experiment controllers to monitor the process as it occurs, and to vector aircraft to begin immediate sampling of pre- and post-convection air mass aerosol characteristics.

IMAGE PROCESSING

The routine processing of SMS/GOES imagery is geared toward displaying high brightness, high contrast scenes containing clouds. More gossamer features such as haze are not always emphasized in prints obtained by satellite image receivers used in operational weather offices. By proper printing techniques, using 10"x10" archival quality negatives obtained through NESS (National Environmental Satellite Service), the haze can be more easily seen. This however involves the added steps of a darkroom procedure interfering with the real-time acquisition of the pictures. A digital technique

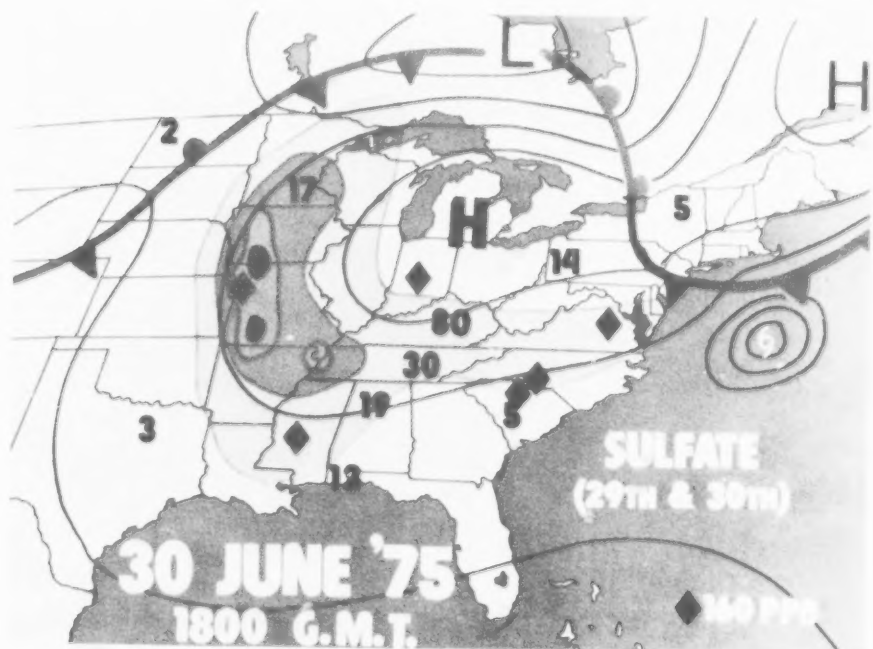


FIGURE 12—Synoptic map, 1800 GMT, 30 June 1975. Shaded areas represent visibility contours of 6, 4, 3, and 2.7 n.mi. NASN sulfate values ($\mu\text{g}/\text{m}^3$) recorded during June 29 and 30 are shown, and triangles mark oxidant monitors which recorded maximum hourly values in excess of 160 PPB.

has been developed by NESS as reported by Parmenter (1977) which is analogous to the temperature enhancement of IR satellite data to delineate the subtly different visible radiances of polluted versus clean air masses. A digital enhancement curve, similar to those applied to infrared imagery, was found very useful. Figure 13 shows an example of the NESS technique. The top panel is a segment of a 2 km resolution image over Florida, as would be seen on a standard weather office satellite receiver. Application of the digital enhancement makes the band of turbid air across the central part of the peninsula and surrounding waters highly visible (middle panel). Reported surface visibilities were under 7 miles within the haze band. Sufficient solar insolation was reflected as to cause a significant differential in ground heating, as evidenced by the suppression of afternoon convection beneath the haze band (lower level).

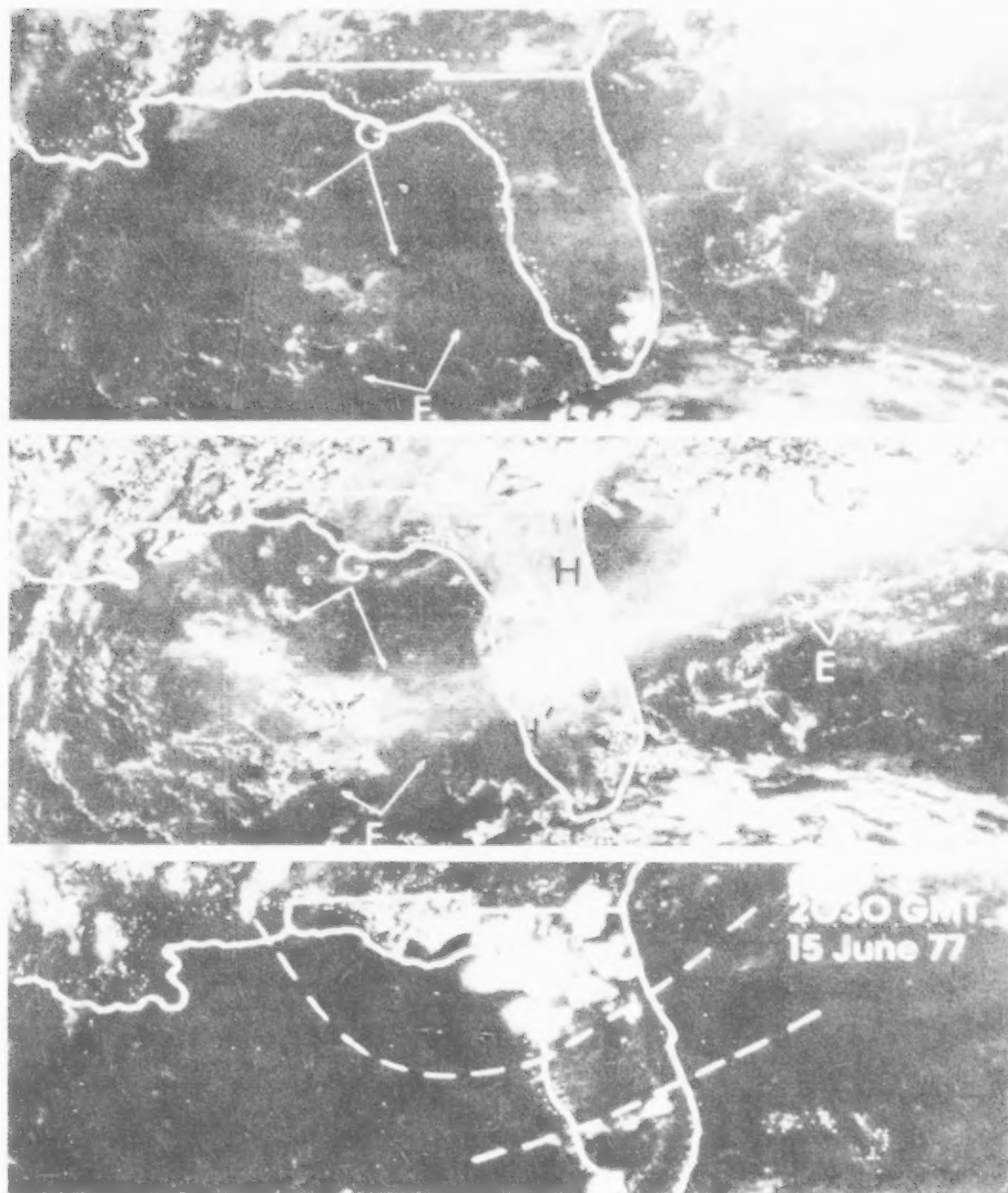


FIGURE 13—(a) Portion of SMS/GOES 2.0 km resolution visible image over Florida, 1230 GMT, 15 June 1977. (b) Same scene, but with imagery digitally enhanced using experimental technique developed by National Environmental Satellite Service. Band of hazy air now distinct. (c) Same region, but at 2030 GMT, 15 June 1977. Haze was sufficiently dense to apparently suppress afternoon convection, present both north and south of haze band. Reproduced from Parmenter (1977).

PROBLEM IN HAZE DETECTION

Another test of the technique was produced on 14 May 1977, when a clean polar air mass descended into the northeast U.S., causing a displacement of a stagnant, polluted anticyclone (Figure 14). The enhanced image at 1230 GMT (Figure 15) shows a clear demarcation of the two air masses, especially over the ocean areas. This effective digital technique, however, is not routinely available from NESS. Thus researchers studying such phenomena must rely on darkroom enhancement of prints made from negatives, or special processing of live or recorded digital satellite data on special image analysis systems. The problem in sulfate haze detection is therefore not one of satellite sensor capabilities, but in ground image processing techniques.



FIGURE 14—Surface weather map, 1200 GMT, 14 May 1977.



FIGURE 15—SMS/GOES 2.0 km resolution visible image, 1230 GMT, 14 May 1977, specially enhanced by computer processing at NESS. A sharp discontinuity in atmospheric turbidity is clearly found at the front separating the two anticyclones. Image courtesy of NOAA/NESS.

THE AUGUST 1976 EPISODE

A major episode occurred from 16 to 29 August 1976 over the eastern U.S. and the adjacent Atlantic waters. This was discussed in detail by Lyons et al (1978). Figure 16 shows the blob on 22 August 1976. It extended far eastward into the Atlantic, as far west as Kansas, and southward through the Mississippi River Valley. The southeastern states were free of haze at this time. Of greatest significance is the sharp boundary of haziness stretching from southern Minnesota across Lake Huron. This precisely marked the polar front with 3.5 n.mi. visibilities to the south and 15+ n.mi. to its north. Figure 17 is a map of the 1800 GMT, 28 August 1976 weather conditions, with contours of the 5 and 3 n.mi. visibilities (corrected for precipitation),

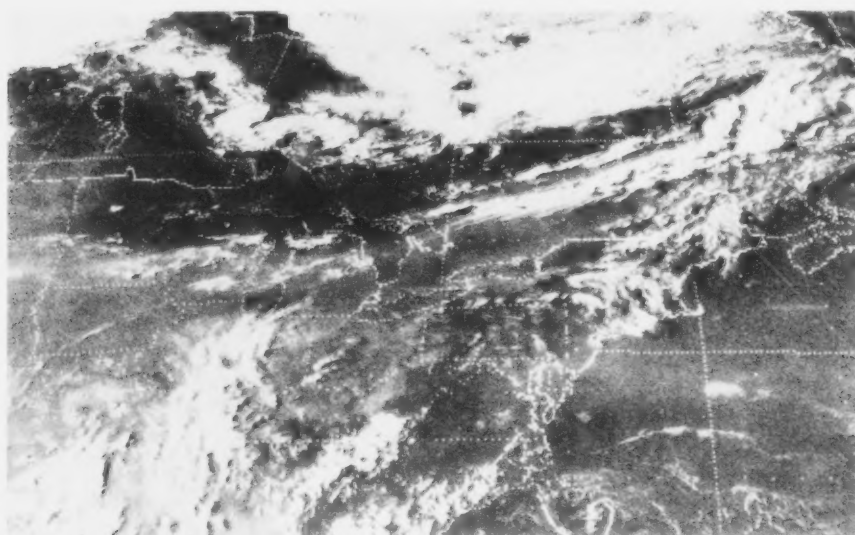


FIGURE 16—SMS/GOES 2.0 km resolution visible image, 2230 GMT, 22 August 1976, showing widespread smog blob stretching from Kansas eastward into the Atlantic Ocean, with a sharp discontinuity along a cold front stretching east-west across the Great Lakes.

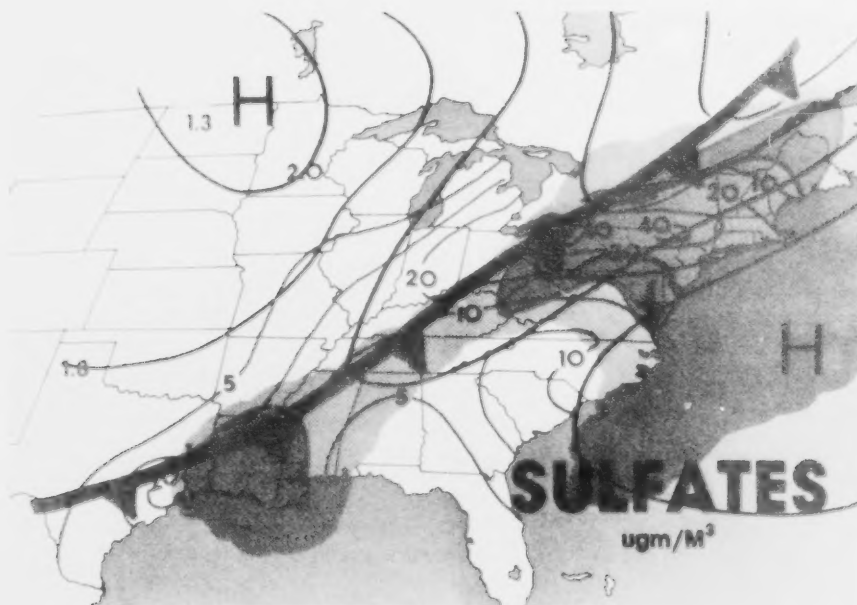


FIGURE 17—Synoptic map, 1800 GMT, 28 August 1976. Overlain on the hazy area outline as seen on the satellite image, and 3 and 5, n.mi. visibility contours are the observed NASV sulfate readings ($\mu\text{gm}/\text{m}^3$). Readings in excess of $40 \mu\text{gm}/\text{m}^3$ were found in low visibility air in Pennsylvania and New York.

and the boundary of the hazy area seen on the satellite picture. This analysis was performed for 13 days of the episode. In virtually all cases, the 5-n.mi. visibility contour lay inside the visible boundary of the hazy blob. It appears that as regional visual ranges drop below 6 or 7 n.mi., the haze becomes visible in properly printed SMS/GOES images, especially over water and other low-albedo targets.

24-HOUR SULFATE MEASUREMENT

Figure 17 also shows the overlain isopleths of NASN sulfate data measured over a 24-hour period ending 1800 GMT, 28 August 1976. The areas of Pennsylvania and New York State, where the visibilities were generally lowest and the image appeared haziest, were associated with 24-hour sulfate levels between 30 and 50 $\mu\text{gm}/\text{m}^3$. The sulfate readings made within the hazy area seen on 28 August, 2230 GMT image, averaged 22.7 $\mu\text{gm}/\text{m}^3$ but outside the haze area were only 5.7 $\mu\text{gm}/\text{m}^3$. Similarly, a series of sulfate measurements were made in New York City by Brookhaven National Lab during this period. When the blob as seen on the satellite prints covered the area, sulfates averaged 23.7 $\mu\text{gm}/\text{m}^3$, but were only 7.5 $\mu\text{gm}/\text{m}^3$ when clean air covered the area (Figure 18). This suggests overall enhancements of sulfate within satellite detected hazy blobs of 3.98 or 3.16 times for these two cases. Similarly, for each of the 13 episode days, the highest hourly ozone measured at all stations reported in the National Aerometric Data Bank were plotted. The average for those sites outside the visible blob was 69.4 PPB, but inside rose to 90.8 PPB, or 30% higher. This suggests that the correlation of hazy, low visibility air to sulfates is stronger than to ozone levels. This is partly due to the apparently greater spatial variability of ozone, as a result of local NO_x sources, etc. Table 1 summarizes these values. Also included are mean values of b_{scat} averaged over the eastern U.S., using 1800 GMT visibilities (with precipitation, fog and high relative humidity samples removed). The mean b_{scat} value compiled by Rudolph Husar of Washington University appears to be a useful measure of "episodicity". Values above 3.5 suggest a widespread and/or intense PEPE in progress.

DATA ANALYZED QUANTITATIVELY

SMS/GOES data can be analyzed quantitatively, using such systems as the McIDAS—Man Computer Interactive Data Access System—developed by the University of Wisconsin's Space Science Engineering Center. Digital data tapes from the August 1976 episode were archived under special EPA funding. McIDAS allows total pixel-by-pixel manipulations of the imagery. All scenes are navigated and grided, with animation of sequential images easily accomplished via rapid access from a video analog disk. A cursor allows the operator to select any number of image pixels and measure the digital brightness counts (DBC, Range 1-256), which can, by application of calibration procedures, be converted into radiances. Over water, with apparently clean air masses present (and confirmed by nearby land visibility of 7 miles or more), DBC's typically ranged from 40 to 45 units. In hazy but otherwise cloud free areas, values would usually range from 70 to 85 DBC's. Thus the signal of a hazy air mass in the SMS/GOES data was clearly well out of the noise level. Over land, typical values in high-visibility polar air masses during August would be around 60 to 80 DBC's, but could be as much as 50% higher when apparent haze covered the target. By careful selection and calibration of ground targets, it appears plausible to use digital satellite data to routinely obtain a measure of atmospheric brightness, and thus of turbidity, visual range, and to a lesser degree, sulfates. What the technique lacks in precision it would appear to compensate for in terms of spatial and temporal coverage - particularly over water, where virtually no routine air quality measurements exist. McIDAS also processes all available surface and upper air meteorological data. These can be processed in real-time, and displayed directly on the satellite imagery. Such useful items as contoured temperatures, surface wind streamlines, 5,000-ft winds, etc. are just a few of the multitude of outputs available.

CONCLUSION

The current generation of meteorological satellite data, in photographic and especially digital form, are capable of synoptic monitoring of the formation, growth, and movement of large-scale hazy blobs known to be correlated with elevated sulfate episodes. Details of the long-range transport and removal process can also be studied.

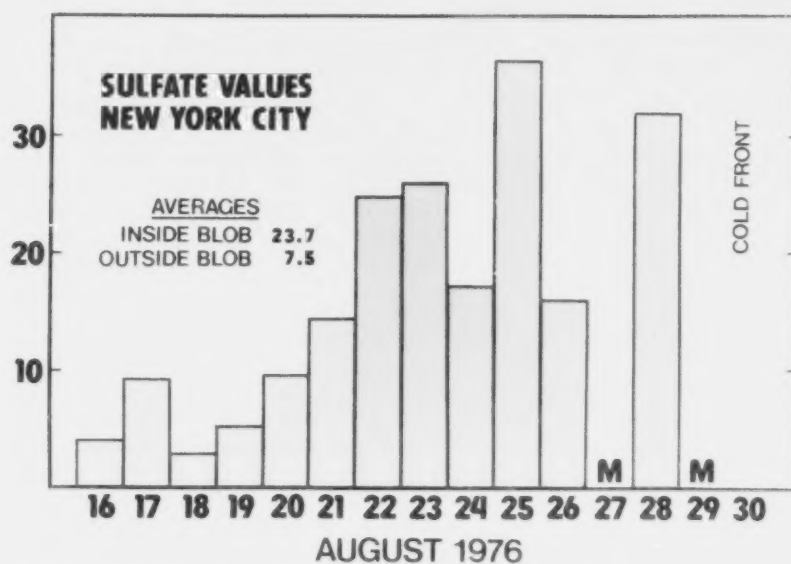


FIGURE 18—Sulfate values, 24-hour averages, recorded in New York City, by Brookhaven National Laboratory from 16 to 28 August 1976. N indicates "smog blob", as seen on the satellite, was not over the area. Y or E indicates the monitor was in or on the edge of the smog blob.

TABLE 1

Average of maximum hourly ozone reports inside the "blob" as seen on the enhanced SMS imagery (PPB), for all NADB stations east of 100° W. Also, the mean b_{scat} determined from NOAA visibility reports over the eastern U.S. (Source: R. Husar, Washington University), August 1976.

Date	b_{scat} ($\times 10^{-4} \text{ m}^{-1}$)	O ₃ Inside (PPB)	O ₃ Outside (PPB)
August 16	2.98	—	—
August 17	2.44	69	69
August 18	2.47	85	65
August 19	2.52	94	66
August 20	3.00	97	81
August 21	3.12	106	107
August 22	3.35	106	67
August 23	4.10	89	77
August 24	4.20	100	65
August 25	5.02	103	57
August 26	4.65	93	77
August 27	4.36	72	57
August 28	3.59	76	54
August 29	2.41		
AVERAGE		90.8	69.4

Figure 19 shows a front of haze moving southwestward along the Atlantic coast on 25 August 1976. This feature was tracked for 3 days and finally disappeared on 26 August, after being advected into a line of thunderstorms along the Florida peninsula, where its aerosols presumably underwent washout.

The satellite data allow for rational extrapolation of surface visibility and sulfate measurements, particularly over water, as well as provide a context for the analysis of aircraft data. Tracking well-defined structural haze features provides a possible means for verifying trajectory and transport models. The export of polluted air masses into, and possibly across, the Atlantic can be studied. (The European METEORSAT satellite provides a similar capability in the eastern Atlantic). Actual digital processing of the SMS/GOES data allows for the testing of statistical and physical models relating atmospheric turbidity, visual range, and sulfate aerosol content.

Real-time data access, processing, and display systems, such as McIDAS, allow the researcher to compile available satellite and meteorological information about PEPE's in an easy to manipulate and evaluate form. The basic software can be augmented by addition of pollution emission inventories, addition of forecasted boundary layer winds and trajectories (from LFM model outputs of the National Meteorological Center), and predictions of future pollution patterns available from existing regional models. The ability of such systems to process and display these data in real-time allows for a vastly improved system of monitoring synoptic scale pollution events—and therefore is a valuable management tool for planning and directing field data gathering projects. Also data and analysis needed for later research can be assembled and error checked "on the fly," thus compiling a real-time climatology and limiting costly data archival and retrieval costs.

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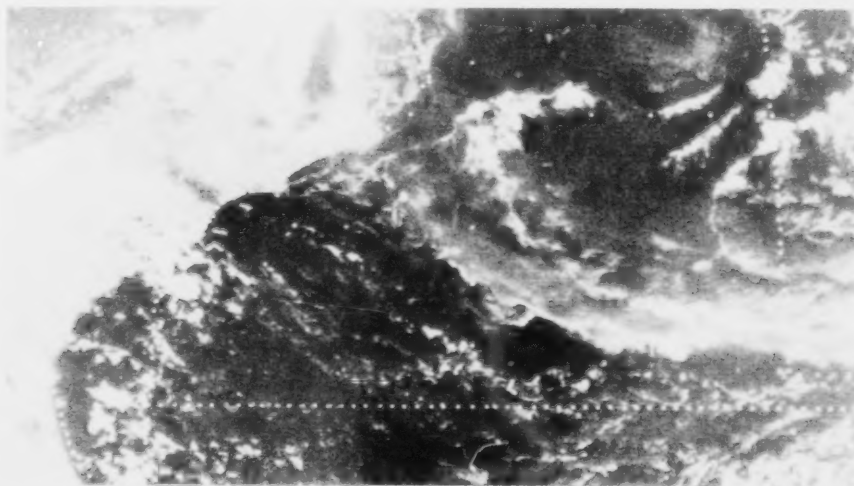


FIGURE 19—Portion of 2.0 km resolution visible image, 2230 GMT, 25 August 1976, showing a front of turbid air moving south and west off the U.S. Atlantic Coast

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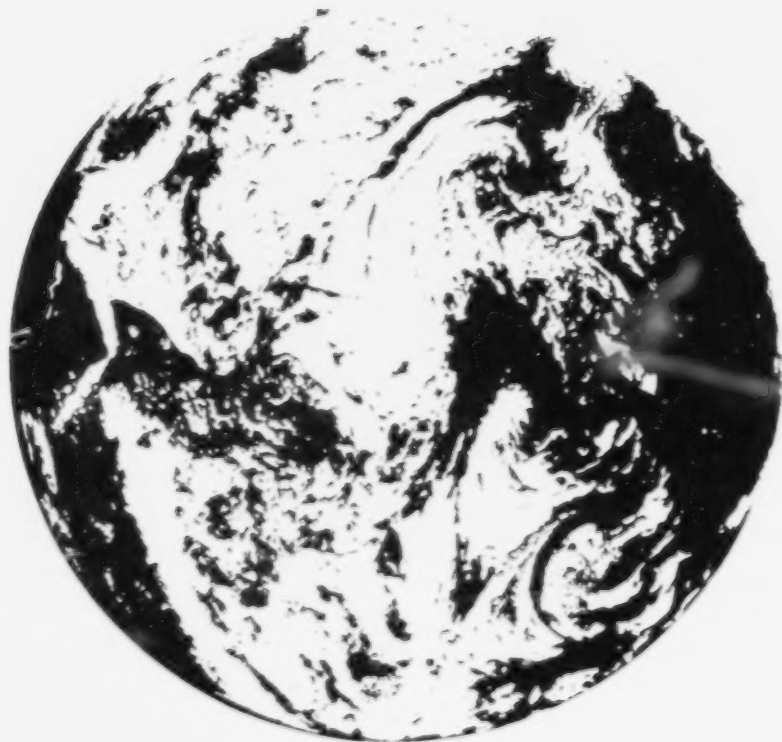
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William E. Wilson, Jr.

STATUS REPORT ON PROJECT VISTTA

(Visibility Impairment Due to Sulfur Transport
and Transformation in the Atmosphere)

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INTRODUCTION

The Clean Air Act Amendments of 1977, in Section 169A, state that "Congress hereby declares as a national goal the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class 1 Federal areas which impairment results from man-made air pollution." Project VISTTA was initiated by EPA's Environmental Sciences Research Laboratory in response to this congressional mandate. The first phase of VISTTA, conducted during FY 1977 and FY 1978, emphasized studies of trends, sources, and characteristics of visibility reduction in Western Pristine Areas, especially the four-state area including New Mexico, Arizona, Colorado, and Utah. The second phase of VISTTA has as its primary objective the evaluation of an existing plume blight model. Data for this purpose will be collected in field studies planned for July and December of 1979. In the third phase of VISTTA, planned for FY 1979, field data will be collected and used to evaluate a regional model of visibility reduction. This paper will provide some background information on visibility, report some results from VISTTA Phase I, and describe plans for VISTTA Phase II.

BACKGROUND

The most obvious air pollution effect is visibility reduction. The human eye is, in effect, the reference method for measuring visibility reduction. Visibility is also the best understood of all air pollution effects. Visibility is reduced by light scattering by small particles in the air, light absorption by particles, and light absorption by nitrogen dioxide. Cause and effect have been clearly established, both theoretically and empirically. Quantitative measurements have been made of the influence of pollutant parameters such as particle size and refractive index and environmental parameters such as relative humidity and sun angle. Much of this information has been documented in two recent publications—*Visibility Protection for Class 1 Areas: The Technical Basis* (1) prepared for the Council on Environmental Quality (CEQ) by Robert Charlson and colleagues at the University of Washington (Seattle, WA) and based on research

sponsored by EPA and its predecessor agencies over the past 20 years; and *The Report to Congress on Visibility* (2) prepared by EPA's Office of Air Quality Planning and Standards (OAQPS) based on contributions from scientists much of whose research was also supported by EPA's Office of Research and Development. It is worth emphasizing that the present understanding of visibility reduction is not due to a crash program initiated when Congress passed Section 169A but is due to the fact that EPA's Office of Research and Development, and its predecessor agencies, have funded over the last 20 years a modest but continuous fundamental research program on the physical, chemical, and optical properties of aerosols. As a result of this work we understand very well the interrelationships between pollutants and the visual quality of the air and can plan effective control strategies.

PROJECT VISTTA

The overall objective of VISTTA is the quantitative prediction of the effect of sources, especially power plants, on visual air quality in Western Pristine Areas. The objectives of VISTTA-Phase I are:

- To determine long-term trends in visual air quality in Western Pristine Areas and to associate visibility reduction with specific pollutants.
- To characterize the visibility-reducing aerosol in Western Pristine Areas with respect to particle size, chemical composition, and spatial distribution.
- To characterize the emissions from power plants, smelters and urban plumes, sources which along with natural background are thought to be most important in reducing visual air quality.
- To utilize information on the size and composition of ambient and source emissions to estimate the contributions of the various sources to visibility reduction.

VISUAL AIR QUALITY TRENDS

Human observers with the National Weather Service make hourly measurements of visibility distance at over 200 weather service stations across the United States. Twenty five years of such data have been analyzed to determine trends in visual air quality. The trends in the more polluted eastern United States are clear and dramatic (3,4). Trends in the Western Pristine Areas, while not so obvious, still show a general pattern of decreasing visibility from 1954 to 1971 followed by an improvement between 1971 and 1975 (5,6). Historical visibility trends are shown in Figure 1 for

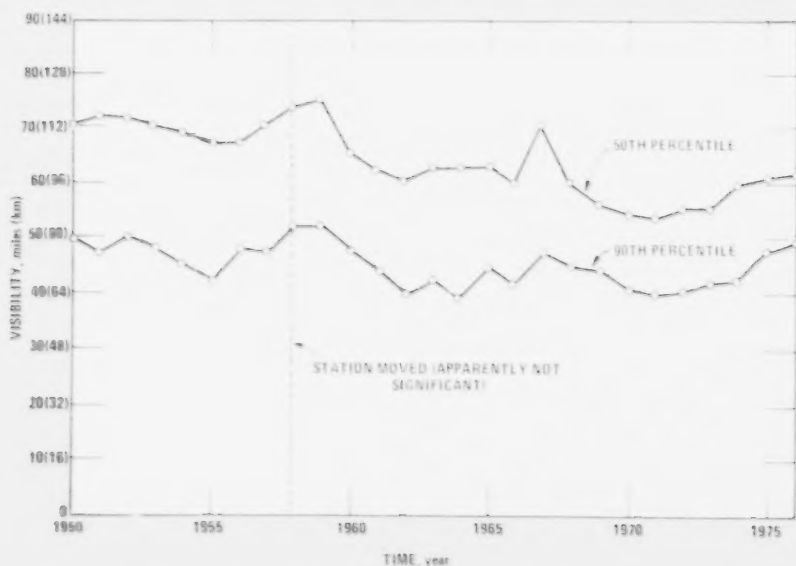


FIGURE 1—Long term visibility trends at Tucson, Arizona, 1950-76

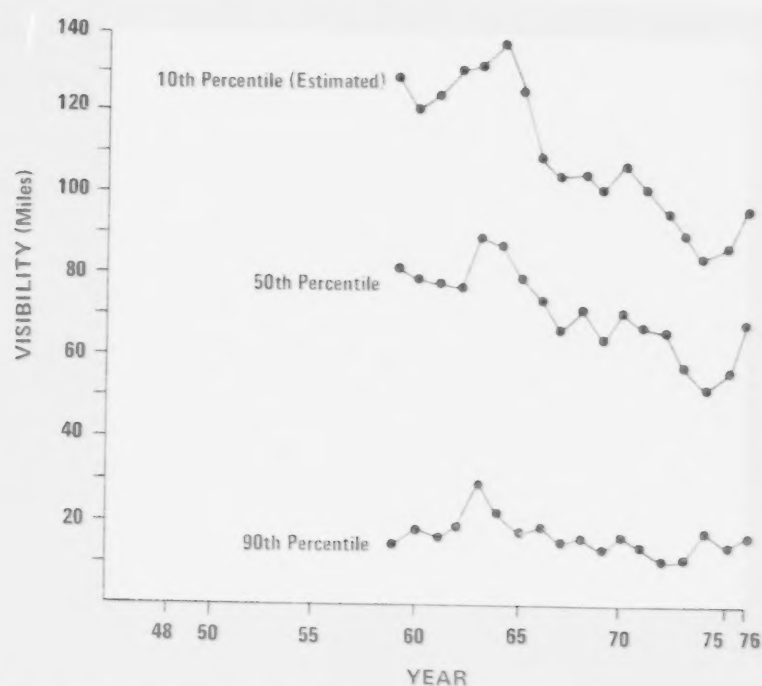


FIGURE 2—Long-term visibility trends at Cheyenne, Wyoming

Tucson, Arizona, an urban site, and Figure 2 for Cheyenne, Wyoming, a nonurban site. In Tucson, median visibility distance dropped from near 70 miles in the 1950's to 55 miles in the years around 1970 followed by an improvement to nearly 65 miles by 1976. The median visibility distance in Cheyenne dropped from the neighborhood of 80 miles in the early 1960's to 50 miles by 1974 followed by an improvement to 70 miles by 1976. In Table 1 changes in the 3-year averages of median visibility distances for 1970 to 1972 and 1974 to 1976 are shown for the 12 sites for which adequate visibility measurements are available. For the Arizona, Nevada, and Utah sites, the

TABLE 1
Changes in three-year averages of median visibility distances

	1954-71	1971-75
URBAN		
Phoenix, Arizona	-23	+12
Tucson, Arizona	-22	+12
Denver, Colorado	-13	+7
Salt Lake City, Utah	-22	0
NON-URBAN		
Prescott, Arizona	-25	+7
Grand Junction, Colorado	-4	+3
Ely, Nebraska	-42	+18
Cheyenne, Wyoming	-23	+12

improvements in visibility from 1974 to 1976 are thought to be due to decrease in SO_2 emissions from smelters. Reasonable correlations have been obtained between SO_2 emissions and visibility distances (6). Regression analyses for Western Pristine Areas indicate that the mass of sulfate, nitrate, and remaining total suspended particulate matter are all required to obtain good correlations between visibility distance and pollutant concentrations (5).

AEROSOL CHARACTERIZATION

The extinction of light caused by particles is due partly to absorption and partly to scatter. Absorption is not a strong function of particle size, but as shown in Figure 3 scattering does depend strongly on the size of the particle. The scattering peaks between 0.2 and 1.0 micron diameter, which is also the size at which the mass concentration of fine particles peaks. A particle distribution measured in Phoenix (7) and the calculated light scattering are shown in Figure 4. Even though the coarse particle

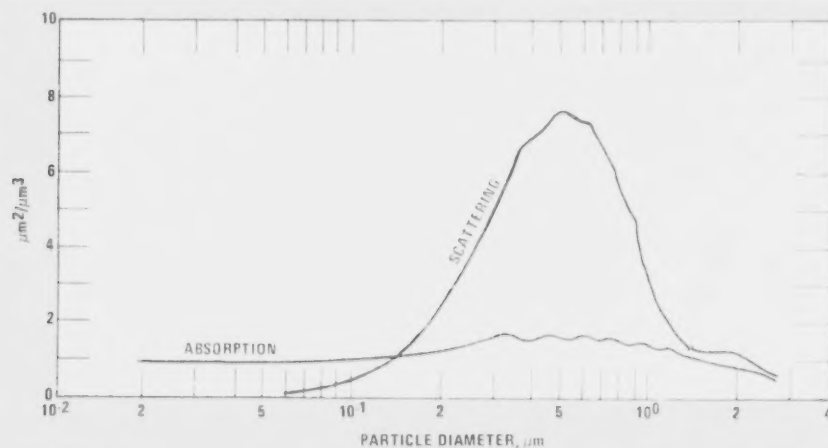


FIGURE 3—Scattering and absorption coefficients per unit volume as a function of particle size; $n_1 = 1.5$, $n_2 = 0.05$ at 550 nm

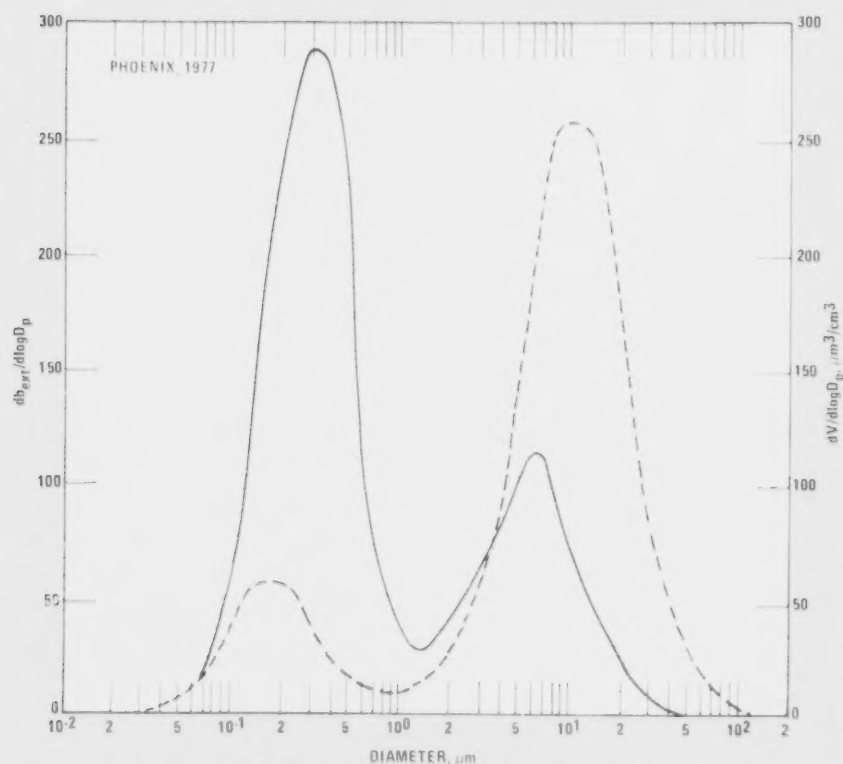


FIGURE 4—Size distribution and light scattering from an urban aerosol, Phoenix, Arizona

concentration is many times that of the fine particles, coarse particles are responsible for only a small part of the light scattering. Rural measurements such as are shown in Figure 5 have a much smaller concentration of coarse particles, and a correspondingly greater portion of the light scattering is due to the fine particles. Light scattering as a function of size for a rural aerosol measured during a regional flight is shown in Figure 6 (8).

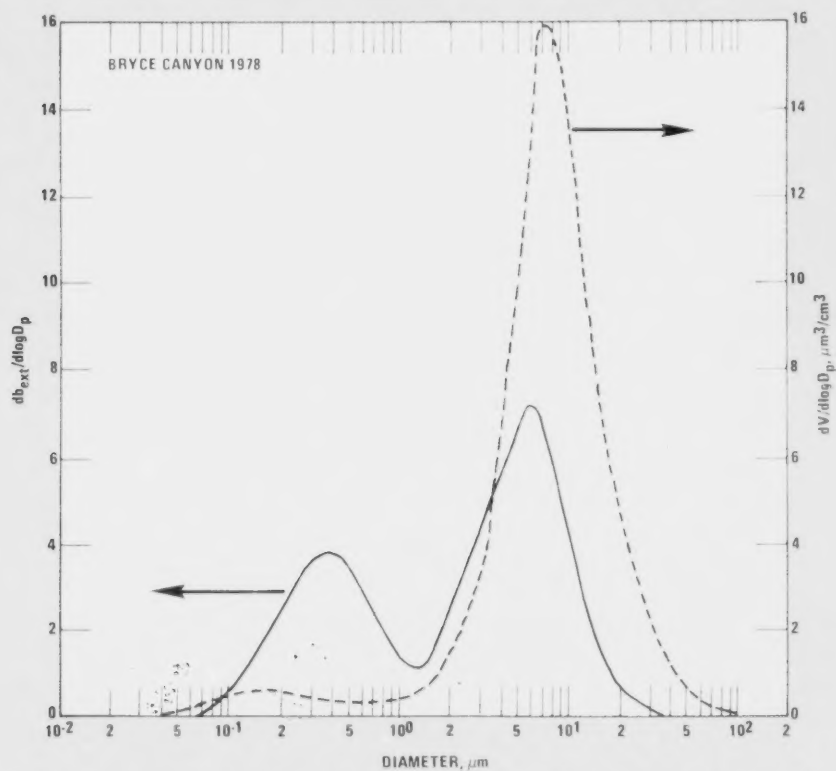


FIGURE 5—Size distribution and light scattering from a non-urban aerosol, Bryce Canyon, Colorado

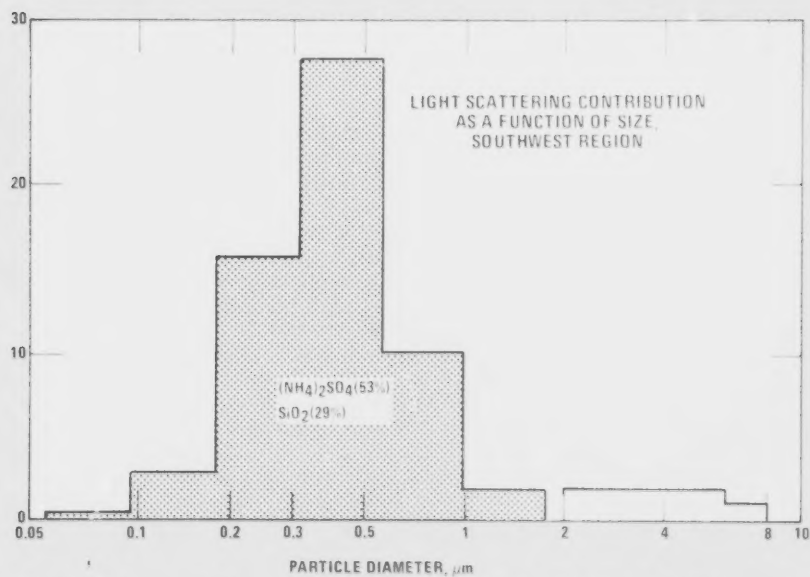


FIGURE 6—Light scattering as a function of size for average aerosol size distribution measured during a regional flight

AEROSOL COMPOSITION

The composition of the coarse and fine aerosol fractions from a regional flight is shown in Figures 7 and 8. Crustal material, SiO_2 , Al_2O_3 , CaO , and Fe_2O_3 , make up a majority of the mass of the coarse particles. For the fine particles sulfate and silica (SiO_2) are the major species with carbon (soot and organic aerosols) and other species making appreciable contributions. Of special interest is the large amount of silica in the fine particle fraction. Substantial amounts of fine particle silica were found in regional aerosols and in smelter plumes, with somewhat lesser amounts in power plant plumes. The fine particle silica appears to be due to condensation of vapor rather than being a tail of the coarse particle size distribution and may be generated during the combustion process. Fine particle silica has been observed by other investigators using the electron microscope but has not previously been attributed to anthropogenic sources (9). The possible existence of fine particle silica in emissions from combustion sources needs to be confirmed by other measurements and analytical techniques. However, if confirmed, this would affect control strategy since fine particle silica might not be effectively removed by scrubbers installed to reduce SO_2 emissions.

CHEMICAL ELEMENT BALANCE

There are two basic techniques for inferring the contribution of various sources to the atmospheric loading of particles and the resulting visibility reduction. One is predictive modeling, which can apply to any specific source, existing or planned. The other involves inferring the source from a knowledge of the composition of particles emitted by a variety of sources and the characteristics of the ambient aerosol. As originally developed by Professor Friedlander it is known as the Chemical Element Balance Technique (10). It can be augmented by information on chemical compounds and particle shape determined by microscopy. When the composition of source emissions is unknown, sources may sometimes be inferred by a statistical technique, factor analysis, which can ascertain which elements vary together and may therefore come from a specific source or source type.

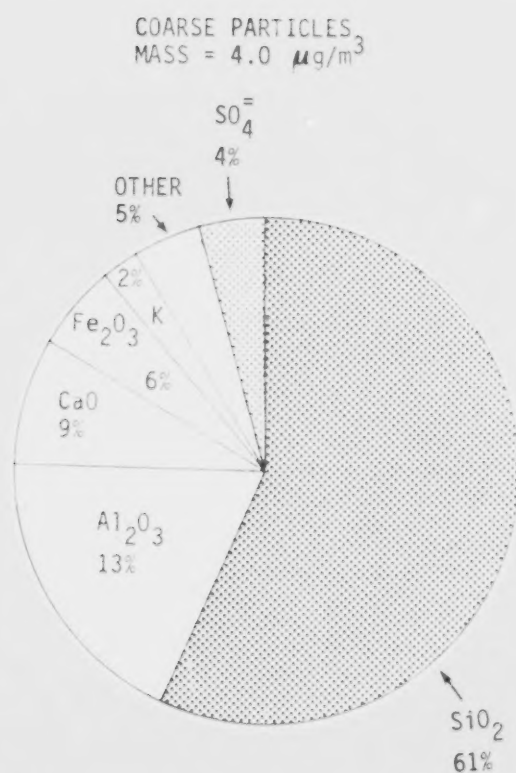


FIGURE 7—Composition of coarse particles collected during a regional flight

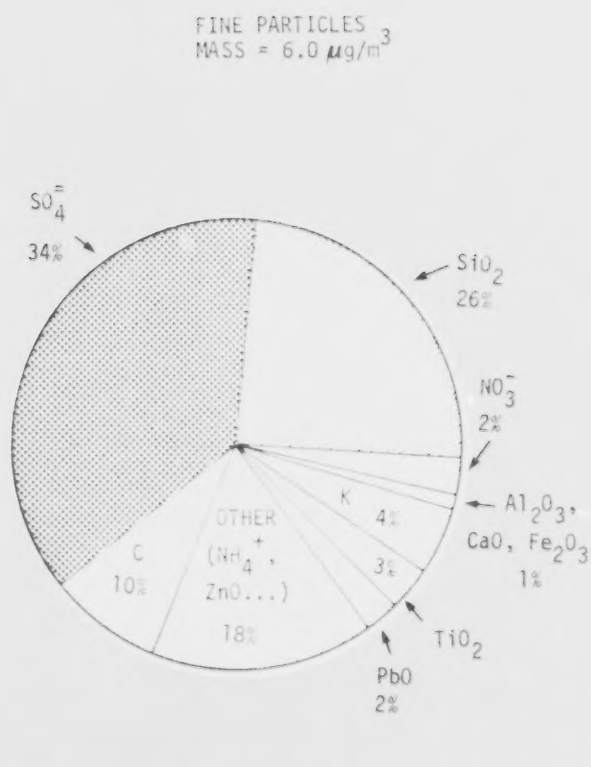


FIGURE 8—Composition of fine particles measured during a regional flight

It is hoped that the composition and size data obtained in the VISTTA study may be used to determine the relative contributions of what are thought to be the major sources: power plants, smelters, urban plumes, and background. This procedure is shown schematically in Figure 9. The major problem areas in applying this technique are inadequate knowledge of smelter and background aerosols and differentiating the various sources of soil-like material. Microscopy can be used to differentiate fly ash, urban road dust, and wind-blown desert dust, but this is slow, expensive, and not very quantitative.

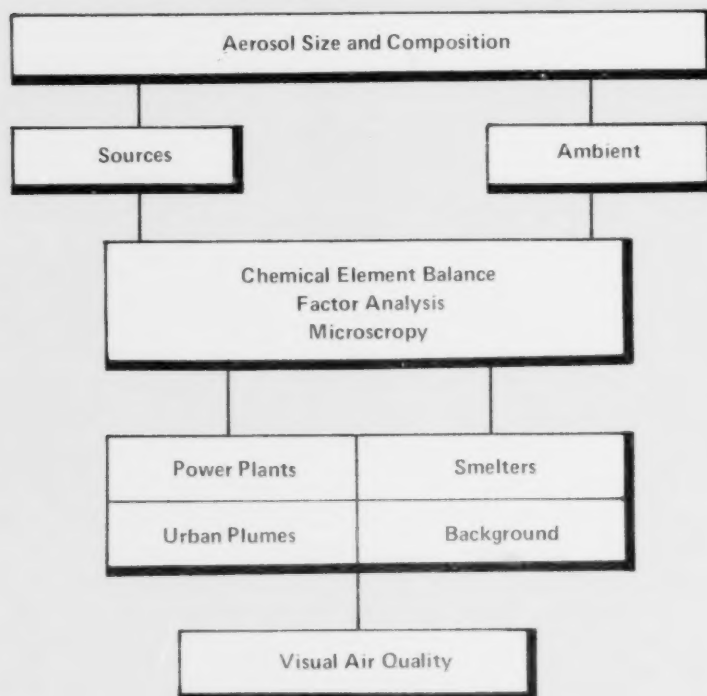


FIGURE 9—Source apportionment

PREDICTIVE MODELS

Predictive models provide another technique for determining the contribution of an existing source to existing visibility reduction. They have the added advantage that they can predict the effect of a projected new source. However, their accuracy cannot be estimated without sensitivity studies and validation by comparison of field measurements with predictions. The components of a visibility model are shown in Figure 10. One asterisk means the process or parameter is fairly well understood, two asterisks mean we have some knowledge and some needed studies are underway, three asterisks mean we do not understand the process and do not have adequate research programs to address the problem.

Ongoing work on modeling has led to reasonable understanding of transport and dispersion over smooth terrain. However, transport and dispersion in the complex terrain frequently characteristic of Western Pristine Areas is not well understood. The gas-phase reactions, which convert NO to NO₂ to nitric acid and SO₂ to sulfate, are fairly well understood from laboratory, smog chamber, and field studies. However, the conversion processes involving gas-aerosol systems such as may occur in clouds are not understood but may be important. There is some information on the dry deposition of gases onto eastern United States type vegetation but inadequate information on dry deposition of particles and dry deposition of gases onto western vegetation and surfaces.

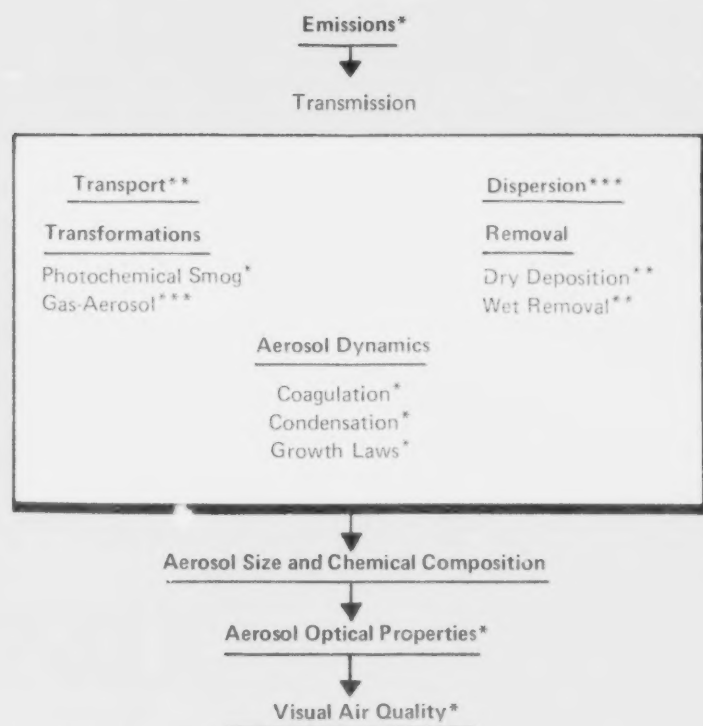


FIGURE 10—Predictive models

Once formation and removal rates are known, aerosol dynamic models should give an adequate estimation of the resulting aerosol size distribution concentration and composition. However, evaluation of the models with field data needs to be done and simplified versions of the aerosol dynamics need to be developed for use in predictive models. The calculation of optical properties (absorption and scattering) is straightforward for ideal, spherical particles. However, work is needed to determine the significance of errors due to nonideality of real particles.

One additional model module is required for a visibility model. A module is needed which uses extinction (scatter + absorption) of particles and absorption of NO_2 to calculate the effect of regional haze or an individual plume on the contrast, color and other optical properties that make up visual air quality. One such module has been developed for Office of Air Quality Planning and Standards by Systems Applications, Inc., for the single plume situation (plume blight model). The primary objective of VISTTA-II is to obtain plume data and use the data to evaluate and improve this model.

VISTTA-I RESULTS

A detailed account of the results from VISTTA-I is given in two MRI reports (8,11) and a paper presented at the New York Academy of Sciences (12). Results from the first VISTTA field study are summarized below:

- On two regional flights over large parts of the Southwest, the visibility-reducing aerosol was quite homogeneous throughout the entire region, indicating that the visibility impairment was of regional character.
- The aerosol size distribution throughout the region on October 5 and 9, 1977, was bimodal, with a geometric volume mean size for the fine particles of ~ 0.25 micron, which is slightly smaller than the continental background aerosol average mean size (0.3 micron). The measured coarse particle mode volumetric mean size was ~ 5.5 microns, which is equal, within error, to the continental background.

REGIONAL AND PLUME IMPACTOR SAMPLES

- The elemental size distribution from both regional and plume impactor samples indicated that aluminum, calcium, and iron are present predominantly in coarse particles; sulfur and titanium are present predominantly in fine particles; and silicon and potassium have substantial concentrations in both modes.
- Sulfur and silicon were found in nearly equal concentrations in the Southwest background data and were the elements present in the highest concentrations in the fine particles ($D_p \leq 1 \mu m$). The detailed aerosol mass balance determined for the Southwest region showed that sulfur (expressed as ammonium sulfate) and silicon (expressed as SiO_2) amounted to ~53 percent and ~29 percent of the fine particle mass, respectively.

PARTICLE SOURCES

- A total of ~93 percent of the measured coarse particle ($D > 1 \mu m$) mass in the Southwest region was composed of elements which were present in the same abundances relative to aluminum as in the earth's crust. This indicates that the source of these particles is either wind-blown dust or material with an elemental composition nearly that of crustal material, such as fly ash.
- The light-scattering budget for Southwest background aerosol on October 9, 1977, indicated that ~52 percent of the light scattering was due to fine particles, ~44 percent was due to Rayleigh scattering from gases, and ~4 percent was due to coarse particles. Considering only the light scattering due to particles, ~3 percent is due to fine particles, which are composed mainly of sulfates (~53 percent as $(NH_4)_2SO_4$) and silicon compounds (~29 percent as SiO_2).
- Mie scattering calculations of light-scattering coefficient due to particles using the measured average regional size distribution were in good agreement with the values measured with a nephelometer. This is a quantitative indication of the internal consistency of the size distribution and b_{scat} measurements which adds credibility to the calculated light-scattering budget.
- Plume excess fine particle aerosol, i.e., the point source emission plume aerosol with the background subtracted, was composed largely of sulfur and silicon compounds for both the smelter and power plant plumes. The major elemental species in the plume excess coarse particle aerosol were aluminum, silicon, potassium, calcium, and iron in approximately crustal abundances in both plumes. These results indicate that fine particle silica may be a good tracer for primary combustion aerosol in smelter and power plant plumes.
- A simple semiquantitative calculation of visual plume impact was performed to determine the visual range with and without the plume present. For the October 4, 1977, flight, the smelter plume caused ~90 percent reduction of visual range relative to the background visual range (135 km) at 8 km downwind from the plant. As far as 127 km downwind, increased b_{scat} and sulfate levels relative to background concentrations were observed, and ~12 percent reduction of visual range due to the smelter plume was calculated. Measurements in the Mohave power plant plume showed ~25 percent reduction of visual range at 60 km downwind on October 8, 1977.
- Sulfate aerosol was formed in Southwest power plant and smelter plumes. The measured SO_2 conversion rate from the San Manuel copper smelter on one morning between 0900 and 1230 (MST) was 0.7 ± 0.2 percent/hour between 60 and 127 km downwind.
- The plume excess visibility budget indicated that fine particle sulfur and silicon species contribute ~53 percent to the excess b_{scat} in the San Manuel smelter plume. In the Mohave power plant plume, coarse particles were the major contributors to the excess b_{scat} , which may have been at least partially due to wind-blown dust on the sampling day.

VISTA-II PLANS

VISTA-II will continue the characterization and source apportionment efforts begun in VISTA-I but will emphasize field measurements to evaluate a plume blight model developed for OAQPS by SAI. The field studies will involve extensive measurements of the optical properties of the plume. Aerosol concentration and size

distribution, light scattering and absorption, and contrast measurements by telephotometer will be made for 3 weeks during June and July and 2 weeks during December 1979. During the December study, photographs will be taken to use in a human perception study.

VISTTA-III

VISTTA-III, which will begin in FY 1981, will emphasize regional visibility reduction and will gather field data to evaluate a number of regional field models.

As a result of fundamental research conducted over the last 20 years we have a good understanding of the interrelationships of pollutants and visual air quality. However, a substantial amount of research remains to be done before we can accurately predict the impact of a single source on visual air quality.

ACKNOWLEDGMENTS

Project VISTTA is a team project directed by the Regional Field Studies Office of EPA's Environmental Sciences Research Laboratory. The groups involved in VISTTA-I and their responsibilities are:

- Meteorology Research, Inc. (MRI)—Project planning, design, and coordination, aircraft sampling, and data analysis
- Aerosol Research Branch, ESRL, EPA—Quality assurance of aircraft measurements
- University of California - Davis (UCD)—Elemental analysis of samples from a specially designed UCD airborne impactor
- University of Washington (UW)—Ground-based measurements of size distribution, light scattering, and light absorption coefficients
- California Institute of Technology (CIT)—Data analysis

VISTTA-I

The following individuals contributed to this program:

Project Coordinator, D.L. Blumenthal (MR)

Senior Data Analyst, E.S. Macias (CIT, Consultant to MRI on leave from Washington University, St. Louis)

Field Manager, J.A. Anderson (MRI)

Data Analysis, B.K. Cantrell (SRI International)

Data Analysis, S.K. Friedlander (UCLA)

Data Analysis, J.A. Ogren (MRI and UW)

Impactor Design and Sample Analysis, D.L. Shadoan, T. Chail (UCD)

Sulfate Analysis, J.D. Husar and Associates

Tom Ellestad, EPA, assisted in the planning of the program and served as project officer for the University of Washington grant.

VISTTA-II

The scientific team has been much expanded for VISTTA-II. Those participating in program planning will be listed here. Dave McNelis, Bob Snelling, and Bill Malm from EPA's Environmental Monitoring and Support Laboratory in Las Vegas have contributed to planning and field activities. The plume blight model being evaluated was developed by Systems Applications, Inc. (SAI) for OAQPS. Steve Eigsti is the EPA project officer. Shepherd Burton, Bob Bergstrom, and David Latimer of SAI are involved in planning the field program and evaluating the model. Personnel from the Salt River Project, operators of the Navajo Power Plant, under the direction of Leroy Michael, Jr., and Prem Bhardwaja, are participating in the study. Will Richards of MRI is field manager for VISTTA-II.

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ENVIRONMENTAL EFFECTS OF ACID PRECIPITATION

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Recent reviews of available data (1,2,3) indicate that precipitation in a large region of North America is highly acidic when compared with the expected pH value of 5.65 for pure rain water in equilibrium with CO_2 (4,5). It has also been shown (6) that the time course of change in pH of precipitation from the mid-1950's to the mid-1970's in the northeastern United States and Canada has been dramatic. Acid precipitation has also spread measurably southward and westward in the United States (1,6). More recent information indicates that, in the southern and western United States, pH values between 3.0 and 4.0 are observed during individual storms (3). Although prior to 1955 the record on changes in acidity of precipitation is very sparse, there are data which indicate that by the mid-1950's precipitation in the eastern United States was already acidic, and that the acidity of rain and snow in that region increased significantly sometime between 1930 and 1950.

ADVERSE EFFECTS

A growing amount of evidence suggests that acid rain is responsible for substantial adverse effects on the public welfare. Such effects include the acidification of lakes and rivers with resultant damage to fish and other components of aquatic ecosystems, acidification and demineralization of soils, possible reductions in crop and forest productivity, and deterioration of manmade materials (7,8,9). These effects can be cumulative or can result from peak acidity episodes (10).

DROP IN pH

A drop in the pH of precipitation has been observed for many years in Scandinavia (11). A monitoring network there has shown that, since the mid-1950's, precipitation in northwestern Europe has increased in acidity and that this acidity is currently widespread geographically. The hydrogen ion concentration of precipitation in some parts of Scandinavia has increased more than 200 fold during the past two decades (12).

SOURCES OF ACID RAIN

Data from New York state and parts of New England indicate that approximately 60% to 70% of the acidity is due to sulfuric acid, and 30% to 40% of the acidity is due to nitric acid. These strong acids are thought to stem primarily from gaseous manmade pollutants such as sulfur oxides and nitrogen oxides produced primarily, although not exclusively, from the combustion of fossil fuels. The relative proportion of nitric acid derivatives and sulfuric acid derivatives may be an adequate indication of the source from which the acid rain was derived; a high proportion of oxides of nitrogen or of nitric acid derivatives would indicate automobile or mobile sources, whereas a high proportion of sulfuric acid derivatives would indicate stationary sources such as power plants, smelters and heavy industry. It is interesting to note that in England in the early part of this century the acidity in the vicinity of Leeds (a heavy coal-use region) was approximately 75% attributable to sulfur compounds (13), and pH in rain and fog appears to have dropped below 3.0 on occasion.

Emission sources for sulfur oxides and nitrogen oxides are widely distributed within and outside urban centers. Contributions can come from stacks, both high and low, and from near ground level sources. Sulfates, including acid sulfates, are present in the stack gases associated with coal-fired and oil-fired sources. The amounts of sulfuric acid and other sulfates found in plumes can be sufficient to affect plume opacity and fallout of acid particles near the source. In plumes from elevated sources, lack of contact with the ground tends to preserve precursors for some distance downwind. At night and in the early morning especially, ground-based inversions can isolate the plume aloft so that near-source deposition is minimized (14).

URBAN PLUME

The urban plume already contains organics, sulfur oxides and nitrogen oxide precursors to sulfates and nitrates (15). Photochemical atmospheric reactions can form sulfates and nitrates relatively rapidly as the urban plume progresses downwind. However, during periods of effective photochemical activity urban plumes will tend to be well mixed all the way to the ground. Therefore, dry deposition processes are competing with atmospheric reactions as sinks for sulfur oxides and nitrogen oxides (14).

In this country, acid precipitation is thought to be most severe in the northeast. Recent data, however, show the problem to be increasing in the southeast and midwest with all states east of the Mississippi affected to some degree. Furthermore, there is recent evidence of acid rain in the western United States, at least in major urban centers such as the Los Angeles area, San Francisco and Seattle (16,17). The ratio of sulfur derivatives to nitrogen derivatives (approx. 2) indicates that acidity in and near urban areas of the west is probably due to automobiles rather than to stationary sources. Precipitation analyses show that the acid rain problem extends into Canada, covering an extensive eastern area as well as a western Alberta region. Unlike more conventional atmospheric pollution, that which gives rise to acid rain may not exceed air quality standards nor cause immediately obvious damage to receptor organisms and materials.

In Canada emissions of SO_2 amount to about 6.5×10^6 metric tons annually, causing concern in three main areas and several smaller ones. The major areas are the Sudbury region of Ontario ($13.7 \times 10^3 \text{ km}^2$), the Windsor-Sudbury-Montreal triangle in Ontario and Quebec ($150 \times 10^3 \text{ km}^2$), and the Grande Prairie-Edmonton-Pincher Creek triangle in southwestern Alberta ($78 \times 10^3 \text{ km}^2$). The isolated centers include Noranda, Quebec; Thompson, Manitoba; Murdochville, Quebec; and Flin Flon, Manitoba. In Sudbury, high ambient concentrations of SO_2 , acting with acid rain and particulates have for many years been a major threat to vegetation and other environmental values. In the Windsor-Sudbury-Montreal triangle, local emissions have not by themselves generated problems, but steady urban-industrial expansion, combined with large emissions in surrounding areas, has caused the normal resilience of environmental characteristics, particularly water bodies, to be exceeded. In southwestern Alberta, emissions from sour-gas processing do not yet constitute a serious threat, but some of the region's agricultural crops are highly sensitive (18).

WET DEPOSITION

From the Canadian precipitation sampling and analysis network (CANSAP), data show that large parts of eastern Ontario, stretching from the Manitoba-Ontario border to Newfoundland, receive substantial amounts of SO_4 in the form of wet deposition

(19). In the more markedly affected parts of southcentral Ontario and Quebec, the amounts of SO_4 being deposited range from 0.6 grams to 2.6 grams of S per m^2 per year. Such deposition rates are less than those in the more severely affected parts of the northeastern United States, but they are about the same as those recorded in Scandinavia where serious damage to the environment has occurred (20).

Serious though these emission and deposition data appear, they become significant only when the nature and properties of the impacted materials are also taken into account. For this reason, precipitation would have to become very acid indeed in the Canadian Prairies to generate environmental concern for calcareous or sulfur deficient soils (21). The same holds for the calcareous and neutral soils of southern Ontario in spite of appreciable sulfate loadings. However, for most of eastern Canada, soils are podzolic, are not well endowed with nutrient elements, and display natural acidities ranging from about pH 4 in the surface horizons to about 5.5 in the lower parts of the profile (22).

BEDROCK GEOLOGY

In general, then, the picture for much of eastern Canada is of a bedrock geology with surficial deposits giving rise to acidic soils and water bodies that are naturally low in alkalinity and calcium reserves. Their neutralizing ability is limited and their resistance to further acidification is severely tested when the strongly dissociated sulfuric acid brought in by acid rain supplants a system normally stabilized by the far less strongly dissociated carbonic and other organic acids.

However, such terrestrial and aquatic systems must not be thought of as being unproductive and of little ecological or economic significance. For the forest resource alone, for example, the direct value (after processing) is about \$4 billion per year, indirect and intangible values in providing recreation, providing habitat for wildlife, stabilizing river flow, preventing erosion and the siltation of water bodies, and furnishing aesthetic appeal are inestimable. Forest growth rates are not as high as in other more favored soil and climatic zones of North America, but this merely means that larger areas have to be more soundly managed than elsewhere.

As the United States increasingly relies on coal as an energy source because of crude oil price and foreign crude oil supply problems, as well as the questionable safety of nuclear power, air emissions from energy producers will increase. Switching fuel from natural gas or oil to coal will make the task of reducing sulfur emissions from new and existing power plants difficult. Mobile and stationary sources of NO_x will also continue to contribute to the loading of acidity to the aquatic and terrestrial environment. In brief, it seems probable that acid deposition to the environment will at least remain at present levels and might be expected to increase over the next decade or two.

LAKE SENSITIVITY

As more coal-fired power plants are built and become operational, especially upwind of the westcentral United States and in the midwest and southeast, the *threshold* of lake acidification may be exceeded. The threshold value for Swedish lakes is an annual average pH depressed to pH 4.6 or below (23). Increased acid loading beyond the threshold value has resulted in more than 15,000 fishless lakes in Sweden.

The transferability of this threshold value for U.S. watersheds (lakes) will depend on the similarity of the environmental factors of the watersheds, and primarily on the lack of acid neutralizing (or alkaline) soils. This single primary factor places limits on the geographic regions which are extremely sensitive to acid precipitation. Lakes in the Adirondack State Park of New York and the Boundary Waters Canoe Area-Voyageurs National Park (BWCA VNP) of Minnesota are examples of such susceptible environments in the U.S. In the Adirondack area the threshold acid precipitation value has been exceeded for many years and as a result, lake pH values are depressed to the point where fish have stopped reproducing and some 90 lakes are now fishless (24).

MAXIMUM SENSITIVITY

In the BWCA VNP, the process of lake acidification is just beginning and only the most susceptible lakes are affected. This area is one that exhibits the properties of maximum sensitivity to acidification due to extremely soft waters, thin soils and very sensitive terrestrial and aquatic plants and animals. In addition, the BWCA is

a wilderness area where the Congress has taken extreme care to preserve the environment against the impacts of *development* (P.L. 95-495). No man-induced changes are desired. As a wilderness area it is also a class I air quality maintenance area under the Clean Air Act.

ACIDIC BEDROCK

The BWCA-VNP region like the Adirondack Park area is found on acidic bedrock which is the main criterion for an acid-sensitive classification (25). Of the midwestern states, only upper Michigan, northern Wisconsin, and northern Minnesota have this type of bedrock covering wide areas (25). The lakes in the BWCA-VNP area have only been surveyed recently for possible impacts from acid precipitation (26) and the results are shown in Figure 1. About two-thirds of the 85 lakes sampled in 1978 and 1979 are susceptible to change from acid precipitation. If these lakes are representative of the 1,500 lakes in the BWCA-VNP, the potential for severe ecological damage is serious. The annual average pH of precipitation in this region is just at the edge of 4.6, and contributions from increasing emissions, including six major coal-fired power plants that are being built or just completed in the area, will certainly increase the rate of acidification.

EXHAUSTED BUFFER CAPACITY

Another measure of the acidification process is shown in Figure 2. Since the major source of acid in precipitation is related to sulfur emissions, the extent of lake acidification has been measured as a function of annual atmospheric loadings of sulfate for lakes in southern Sweden. The sharp drop of this pH curve for extremely sensitive lakes shows how a slow increase in added increments can and will cause a sharp break in the response curve. This response is characteristic of very soft water lakes where only a small amount of bicarbonate is available to neutralize the incoming acid. The pH remains relatively constant until all of the carbonate is consumed and then the stronger organic and sulfuric acids control the lake pH. In other words the assimilative capacity (or buffer capacity) of the lake has been exhausted as indicated by the break point and downward slope, especially, on curve 1 of Figure 2.

The general shape of the sulfate loading-pH response curve shown in Figure 2 is also expected for an individual lake as the acid loading from atmospheric sources is increased over time. For a given region where the loading is fairly constant, the pH response of lakes may be described as a series of response curves, similar to those in Figure 2, each reflecting individual differences and characteristics of the particular lake watershed. Some of the factors which control the shape and displacement of these loading-pH responses are watershed area/lake volume ratio, soil-geology factors, vegetative cover, ground water input, organic acid input from bogs, and a host of other factors yet to be defined. The size of watershed and stream order have also recently been discussed as factors in pH loading (27). If the acid loading to a particular region is limited to the amounts defined by the upper portions of the response curves for sensitive lake systems, the magnitude of the damage to the aquatic environment can be minimized.

EFFECTS ON SOILS AND FORESTS

In 1930, the federal Canadian Forestry Service became involved in terrestrial research on air pollution effects dealing with problems at Trail, British Columbia, and with the separation of pollution effects on forests from those arising from insect and disease attack. Since then numerous signal contributions have been added to the understanding of pollution problems, usually near strong point emitters (28,29,30,31, 32,33). In perspective, although there may seem to be many features common to acid rain and atmospheric pollution regardless of how they originate, there are two important differences. First, long-range pollution usually does not exceed conventional air quality standards. Second, it may not cause any spectacular or immediately measurable reduction in tree growth. A superficial view, therefore, or one based on a ranking in priority of more obvious disasters would fail to discern much of a problem. Early research of H. J. Wheeler in Rhode Island and J. A. Voelcker at Woburn may now seem very distant, but their striking demonstration of the soil acidification, calcium removal, and aluminum solubilization effects consequent upon repeated sulfate fertilizer applications are well documented (34). Indeed, the apprehension is that acid rain could bring about analogous effects leading to permanent reduction in tree growth and site quality. Useful soil microorganisms will be eliminated and potentially toxic soil elements, such as aluminum and manganese, brought into solution to exercise deleterious effects on plant roots and nutrient absorption. Moreover, since heavy metal

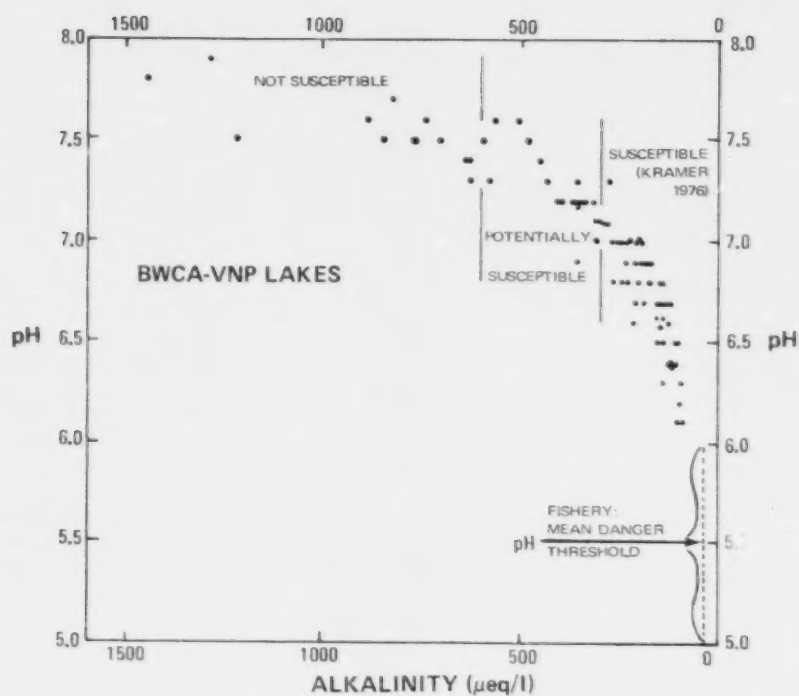


FIGURE 1—The relationship between pH and alkalinity in 85 BWCA-VNP lakes

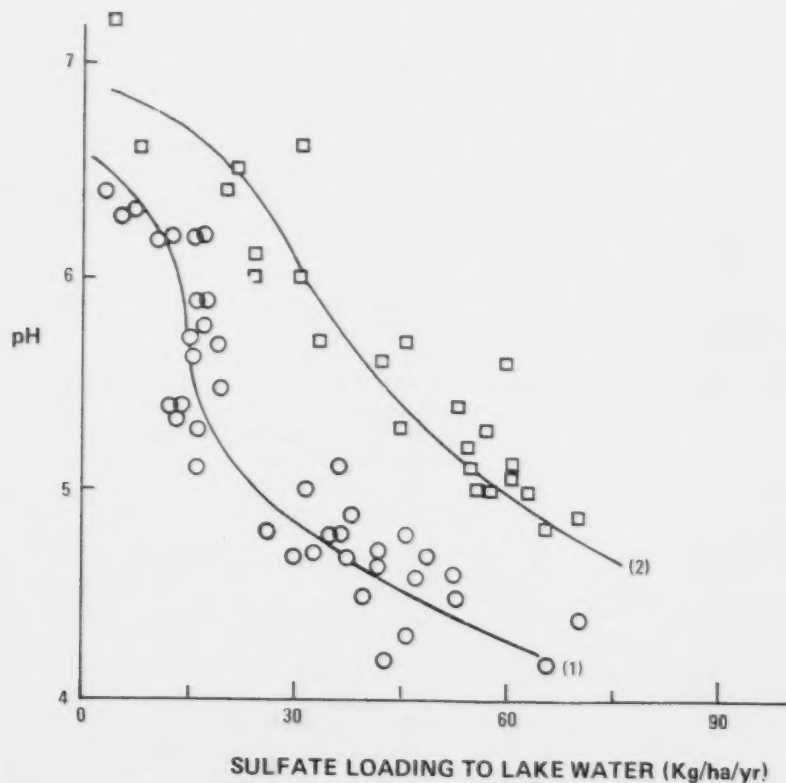


FIGURE 2—Data from lakes in Sweden showing the relationship between acid loading and pH change for (1) very sensitive and (2) somewhat less sensitive surroundings

particulates sometimes accompany gaseous pollutants, a situation could arise that such noxious elements are held preferentially on the exchange sites of colloids at the expense of the more useful monovalent and divalent cations.

Unlike the situation in aquatic systems, however, there is a more acid state of podzolic forest soils, where acid rain may not very readily lower the pH further or induce further losses in bases (35). The complex makeup of soils prevents the pinpointing of a sharply critical soil pH value separating adverse and nonadverse effects of acid rain. However, it seems likely that the approximate value lies within the pH 4.0-5.5 gradient seen in eastern Canada podzol profiles.

NEW APPROACHES

New approaches, not based on strong point emitters, include sensitivity mapping. This can be very crude—such as the separation of areas of calcareous and noncalcareous bedrock or the identification of sulfur deficient soils (21)—or it can be large-scale and based on a synthesis of soil attributes. Considerable progress has been made in grading the sensitivity of Ontario lakes, using alkalinity as an index, and it is possible that a somewhat similar index based on exchangeable calcium status could be used for soils. For at least the reasons that are explained above, however, such a soil sensitivity index may always be no more than a very crude indicator.

Of particular value are lysimetric-type studies in progress by I. K. Morrison and his colleagues at Sault Ste. Marie, Michigan. Representative monoliths are being percolated, with known amounts of simulated rain, to test the rate at which horizons change their properties and the speed of calcium release. Knowing the sulfate loadings such soils are experiencing under natural conditions, the results from such lysimetric installations should permit approximate predictions of soil changes under field conditions.

EFFECTS ON AGRICULTURAL SYSTEMS

There are two basic ways acidic precipitation can impact agricultural crops. First, acidic precipitation can impact directly on the foliar surface of the plant itself causing a direct effect on the leaf or stem of the crop plant. In these cases the most immediate effect is on crops such as lettuce, spinach, or chard for which the foliage is the valuable portion. Second, acidic precipitation can indirectly affect the crop plant through effects on the soil. For example, changing the pH of rainfall which strikes the soil can change the rate at which nutrients are recycled, litter and other organic matter is broken down through microbial action in the soil, and the rate at which both macronutrients and micronutrients are leached from the soil into surface waters or into ground waters. Detailed physiological mechanisms whereby these two basic impacts are manifest have been discussed elsewhere (36).

At pH below about 3.0, areas of leaf surfaces generally become spotted or necrotic. For obvious reasons, vegetables as well as ornamental plants may be unmarketable after exposure to rain or mist at or near pH 3. With decreases in functioning leaf area, the photosynthetic process itself decreases and the productivity of the plant necessarily decreases. It is also true that, with changes in aboveground biomass such as would be experienced under low pH rain, belowground biomass would be similarly decreased. It is not yet known what the relationship is between percent leaf area affected (nonfunctional due to necrotic areas) and percent change in growth for plants. However, it is known that, with depressed pH, foliar losses of important nutrients such as K^+ , Mg^{++} , and Ca^{++} are observed (37,38).

Nutrient cycling changes in either agricultural land or forestry land can result in lowered fertility over the long term as well as decreases in essential soil nutrients which are required for normal plant growth.

ALTERATIONS IN PATHOGENICITY

In three out of five host-parasite systems involving oak trees and kidney beans, alterations occurred in the pathogenicity of the parasite under conditions of artificial sulfuric acid precipitation at pH 3.2. An additional observation was that root nodule number and nitrogen fixation of kidney bean were diminished by sulfuric acid rain at pH 3.2, and that bean yield was decreased in low cation exchange capacity soils but not decreased in higher cation exchange capacity (greater than 3 meq/100 g soil) soils (39).

Rain water at approximately pH 4.0 due to volcanic activity in the Kona district of Hawaii is known to adversely affect tomatoes. While 5 kg per plant of salable fruit was obtained from tomato plants grown under a plastic rain shelter, no salable fruit was produced on plants growing immediately outside the rain shelter (40). While it is possible that gaseous pollutants such as SO_2 may also be present near fumaroles or volcanic activity, the fact that the plastic rain shelter provided enough protection to the plants to permit fruiting indicates that gases alone are probably not the cause. It is possible that the causative agent was not rainfall, but dry fallout. This possibility should be investigated experimentally. However, it has been shown that cations, plant growth regulating substances, and other materials are leached from growing plants by rainfall (41) and that leaching rates increase for many materials as pH decreases (42).

EXTENSIVE SCREEN PROGRAM

While the data relating the effects of acid precipitation on crop yield and production are somewhat sparse, there is every indication that acid rainfall is deleterious. In order to pursue this hypothesis somewhat further, an extensive screening program to look at the effect of sulfuric acid rain on virtually every major field crop of the United States has been initiated by EPA. This study has been undertaken to determine the sensitivity of crops to simulated acid precipitation in an experimental farm facility because of the potential for widespread economic damage to a number of field crops (43). Results from this study are expected by the summer of 1980. Preliminary indications of effect of simulated acid rain on yield of certain early maturing crop varieties such as peas, broccoli, and certain other early crops are expected by fall, 1979.

SUMMARY

In summary, there is substantial reason to suspect that the deposition of acidic precipitation throughout wide geographic areas of the eastern United States and Canada will have adverse effects on aquatic systems, forests, and agricultural systems. Evidence presented in this paper suggests several avenues of research which should be pursued to further define the magnitude and extent of the effects of acid precipitation on resources. The cumulative threat of acid precipitation is recognized and a concerted attack is being spearheaded by Environment Canada and the U.S. Environmental Protection Agency that brings together different disciplines and jurisdictions. Ongoing pollution studies based on strong point emitters and special new investigations are being applied in a number of promising approaches. These include the use of sensitive lichens as indicator species, previsual biochemical tests on tree tissues, differential depositional patterns of pollutants on soils, and delineation of sensitive soils, forests, and water bodies. While direct effects on terrestrial and aquatic ecosystems should be investigated intensively, indirect effects on the abiotic components of such systems should also be studied. For instance, a number of processes involving the impact of acidic precipitation on soil systems, both amended agricultural soils and natural forest soil systems, need to be investigated. Processes such as litter decomposition, nutrient cycling, leaching of nutrients and other cations and anions from natural and managed soil systems should be investigated. Further definition of sensitive areas of the eastern portion of North America should be accomplished so that field research programs can be focused geographically in those areas where the impact is suspected of being greatest.



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AIR QUALITY STUDIES IN SUPPORT OF THE
OHIO RIVER BASIN ENERGY STUDY

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ORBES

The Ohio River Basin Energy Study (ORBES) is designed to assess the potential environmental, social, and economic impacts associated with the construction of additional power plants in the Ohio River Basin. The original study area, as mandated by Congress, included parts of the four states of Illinois, Indiana, Kentucky,



UTILITY GROWTH AND EMISSION

EMISSION AND SITING CONSTRAINTS

and Ohio but has since been expanded to include parts of West Virginia and Pennsylvania. The evaluation of air quality changes for different assumptions of power demand, economic conditions, and regulatory constraints plays a central role in this assessment. From the outset of the study, there has been the concern that the locations of existing and future power plants along the major rivers (see Figures 1 through 3) could lead to elevated primary and secondary pollutant concentrations during periods of persistent winds along these high density siting corridors (1).

The air quality analysis for ORBES is one part of the Integrated Technology Assessment (ITA) process (Figure 4) which forecasts the growth and development of the utility industry as a function of regulatory constraints, electricity demand, economic conditions, and technologies and costs for electric generation and pollution control. The actual projection of utility growth and emissions is carried out by use of the EPA Utility Simulation Model (USM) which was described during the 1978 Interagency R&D meeting (2). The USM emission calculations are then input to an air quality dispersion model along with appropriate meteorological data to obtain estimates of air pollutant concentrations for comparison with applicable standards or use in impact assessment. While this analysis is in principle straightforward, a number of complications arise due to the intricacies of the regulatory process and lack of validated models for certain pollutants and transport scales of interest. For a better understanding of the air quality issues for the ORBES region, the following discussion will deal separately with air quality constraints and impacts.

The Clean Air Act Amendments of 1977 impose certain air quality constraints upon new source emission characteristics and siting. An emission constraint can be viewed as an air quality constraint which deals with individual source characteristics such as stack height, percentage of the pollutant removed, or quality of the fuel burned. Examples of emission constraints are State Implementation Plans (SIP), New Source Performance Standards (NSPS), Best Available Control Technology (BACT), and Good Engineering Practice (GEP) stack heights. Siting constraints, on the other hand, deal with the total emissions from an individual plant or group of plants, possible interactions with other plants in the area, and the potential impact on pollutant nonattainment areas. Siting restrictions are embodied in Emission Offset Rules and Standards for the Prevention of Significant Deterioration (PSD).

As it now stands, the USM considers several air quality constraints in the assignment of future electric generating capacity on a county by county basis: current and

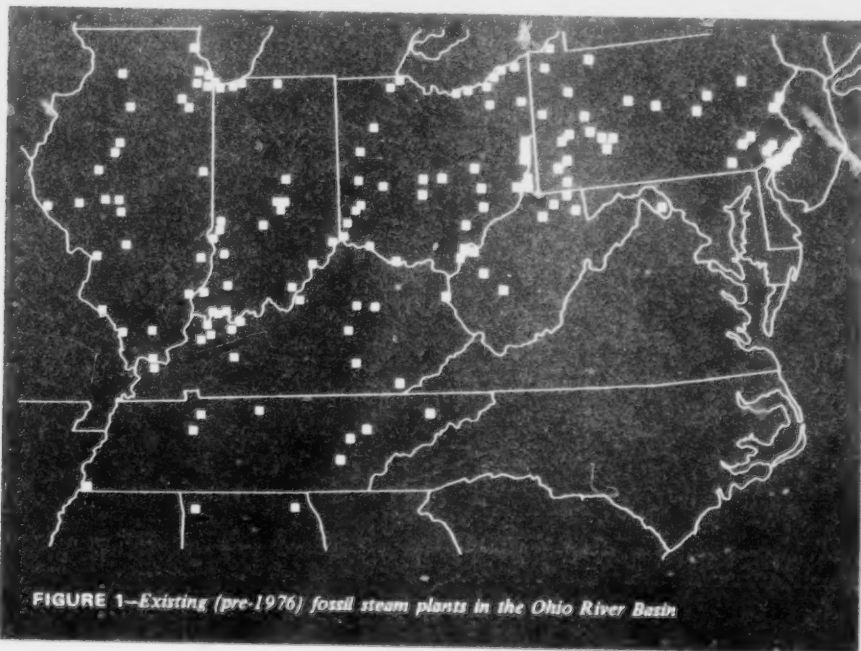




FIGURE 2—Fossil steam units in the Ohio River Basin (1976-1982) in accordance with NSPS



FIGURE 3—Fossil steam units in the Ohio River Basin (1983-2000) projected by the utility simulation model in accordance with the revised new source performance standards

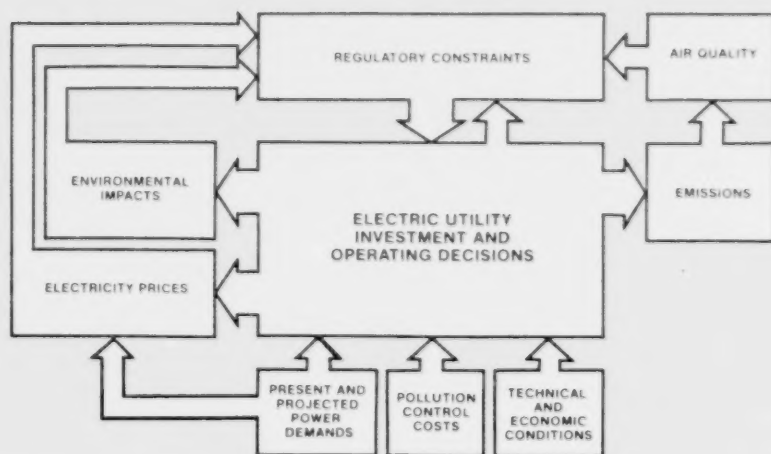


FIGURE 4—The integrated technology assessment of electric utilities

IMPORTANCE OF STANDARDIZED MODELS

revised NSPS, SIP emission limitations for existing plants, and no post-1987 plant siting in the counties designated as nonattainment for sulfur dioxide (SO_2) or total suspended particulates (TSP) or in those counties containing designated PSD Class I areas. An evaluation of other air quality constraints, however, requires the analysis of local or subregional scale pollutant transport which is described through the application of EPA standardized dispersion models. While the existence of these standardized models does not preclude the use of more refined modeling techniques, they are heavily relied upon by federal and state agencies for PSD review and therefore represent a *de facto* air quality constraint. For example, apart from the question of nonattainment, the principal air quality constraint on the growth of coal-fired generating capacity in the Ohio River Basin can be traced to the calculated second highest 3-hour SO_2 concentration under the extremely unstable (A Stability) condition. This relatively high concentration is expected to occur rather close to the plant in question and only over a very limited area so that the chance of additive impacts is remote unless two sources are extremely close to one another. This assumed maximum impact condition allows the construction of additional plants in an area, each with emissions below a certain limit, until the number of plants along the prevailing wind direction is sufficient to exhaust the 24-hour or annual PSD increment for SO_2 in Class II areas (see Table I). This example illustrates the importance of the standardized models in the regulatory process. In recognition of this fact, we now briefly examine some of the basic assumptions and operating characteristics of these models.

TABLE 1
Maximum allowable SO_2 and TSP increments ($\mu\text{g}/\text{m}^3$) under the Rules for Prevention of Significant Deterioration

	Class I	Class II	Class III
Particulate Matter			
Annual geometric mean	5	19	37
24-hour maximum	10	37	75
Sulfur Dioxide			
Annual arithmetic mean	2	20	40
24-hour maximum	5	91	182
3-hour maximum	25	512	700

GAUSSIAN PLUME EQUATION

Calculation of short-term concentrations for comparison with standards is carried out through the application of the steady state Gaussian plume equation on a sequential hourly basis. The vertical and horizontal standard deviation of plume concentrations depends on downwind distance, wind speed, solar elevation angle, cloud cover, and the height of the lowest cloud layer. The parameterization of this dependency is based primarily on experiments involving ground level tracer releases. The vertical dispersion of pollutants is limited by the ground surface and the top of the mixing layer so that for long downwind distances, the concentration becomes uniform within this layer. Morning and afternoon mixing heights are estimated from the early morning temperature sounding and the morning and afternoon surface temperature. Hourly mixing heights are in turn estimated from morning and afternoon mixing heights by use of a stability dependent interpolation scheme. The rise of the plume above the stack top depends on the stack gas exit velocity, gas temperature, stack diameter, ambient temperature, wind speed, and atmospheric stability. The wind speed used in the plume rise and dilution calculation is adjusted to the top of the physical stack by use of a stability-dependent power law. If the effective plume height is calculated to be greater than the height of the mixed layer, then no concentration impact is assumed at ground level for that hour. The effect of terrain is accounted for by reducing the effective plume height by the difference between the receptor and stack base eleva-

HOURLY AMBIENT CONCENTRATIONS

tions. Hourly concentrations are then calculated for a large number of receptor locations around the stack, using 5 years of hourly meteorological input data. These calculated concentrations are then screened to find the highest of all the second highest 3-hour and 24-hour concentrations for comparison with standards. If only 1 year of meteorological data is available, then the highest of all the highest calculated concentrations at each receptor is selected.

From the preceding description of the PSD models, it can be seen that the calculation of an hourly ambient concentration is a somewhat involved procedure. For example, the wind speed not only enters into the calculation of plume dilution, it is also used in the estimation of plume rise and the assignment of atmospheric stability class. In spite of this built-in complexity, however, the critical impact condition for various source types is calculated to occur under well defined meteorological conditions.

The Stability A impact mentioned earlier is one example of a critical meteorological condition for elevated point sources. The dispersion model will make this stability class assignment for the midday hours of spring and summer months when the sky is relatively clear and the winds are quite light. The highest or second highest 3-hour concentration for this impact condition will occur when the wind flow vector falls along the line joining the source and receptor for at least 1 hour or when the flow vector is close to this line for 2 or 3 hours.

MODEL REVISION

While the application of these standardized models acts as a constraint to the siting of new power plants in the ORBES region, it should be noted that these models will in time be revised, even to the extent of changing some of the basic model assumptions. Every 5 years EPA will hold a conference to discuss suggested model improvements. Modifications will be made based upon the results of field studies and the comparison of model calculations with monitoring network data. In addition to these basic changes to the models, guidance is continually provided by EPA regarding detailed model application procedures and the suitability of emissions and meteorological input data. These activities also introduce an element of time dependency into the air quality constraints imposed by the use of these models in the licensing process.

AIR QUALITY IMPACT ANALYSIS

The preceding discussion was designed to indicate the increasingly important role of air quality modeling in the regulatory framework. With the standardization of these models, they have become almost an extension of the regulations themselves. The air quality impact analysis described in this paper, on the other hand, deals with those pollutants and averaging times for which standards exist, but is not restricted to the application of standardized models. In addition, the impact analysis for the ORBES Region addresses those air quality issues for which standards are under consideration. These include the formation and regional transport of sulfate and ozone, visibility degradation and acid precipitation.

As was the case with the analysis of air quality constraints, this impact analysis requires the use of dispersion models to relate emissions to ambient concentrations or other air quality related values. Unfortunately many of these models are designed for specific applications, have large computational and input data requirements, and are not adequately validated. In some cases, the models are still under development or have not been released. Due in part to these problems with the air quality models, the initial portion of the ORBES air quality study was devoted to the collection of emissions, meteorological and air quality data. The ORBES Aerometric Data Base includes the following information:

- Continuous emissions, meteorological and air quality data from member utilities of the East Central Area Reliability Council
- Surface and upper air data from the National Climatic Center
- Tower meteorological data from the Nuclear Regulatory Commission
- Historical sulfate, O₃, and TSP data from the National Aerometric Data Branch

- Emission inventories from the National Emissions Data System, Electric Power Research Institute and Brookhaven National Laboratory
- Satellite photographs for identification of haze layers
- Precipitation chemistry data

ANALYSIS OF SO₂

The continuous monitoring data has been used to provide a realistic picture of existing air quality throughout the region (see Figure 5). In particular, the network data from the American Electric Power System provides excellent geographical and historical coverage for SO₂, NO_x, and TSP. In addition, 8 of the 11 networks have meteorological towers and the remaining 3 have ground based wind instruments. For all of the networks combined, there are a total of 65 SO₂, 14 NO_x, and 64 TSP monitors with at least 3 years of data at each site. Before the acquisition and analysis of this data, the determination of regional SO₂ and TSP concentrations was difficult since much of the data was taken in cities and towns and in many cases only represented measurements taken every 6 days. In addition, very little data was available to estimate peak 3-hour SO₂ concentrations since most of the measurements consisted of 24-hour bubbler samples. The SO₂ and meteorological data from these power plant monitoring networks has also been extensively analyzed to study the influence of meteorological parameters upon the observed hourly concentrations (3). The following information has been obtained from this analysis:

- Cumulative frequency distributions of 1-hour, 3-hour, and 24-hour SO₂ concentrations for each site-year of data. Also given are the mean, standard deviation, and highest and second highest values along with their time and date of occurrence for each of the averaging times.
- Average hourly SO₂ concentrations for each 16 wind directions and 5 wind speed classes. In addition, the yearly frequency of occurrence of 1-hour SO₂ concentrations over 100 μgm^{-3} is specified for each wind direction and wind speed class.
- Relative frequency of occurrence by stability class of a particular wind speed and wind direction range.
- Frequency of occurrence of cases of persistent wind by wind direction class, wind speed class, and duration of persistence. For this analysis, persistence was defined as a period of 7 hours or greater during which the wind direction did not vary by more than 11 degrees and the wind speed by more than 2.5 msec^{-1} .
- Summary of the emissions, meteorological, and air quality data for those days on which the highest 25 daily SO₂ concentrations were reported. For each network-year, 25 SO₂ 24-hour episodes are selected.

RESULTS OF SO₂ ANALYSIS

The preceding analyses are currently being extended to TSP and NO_x concentrations. Some of the most significant results of the ORBES air quality work have come from an analysis of SO₂ episodes observed by these networks. From this analysis a climatology of worst case meteorological conditions has been developed not only for source specific impacts but also for periods of elevated background SO₂ concentrations. In the lower Ohio Valley, the highest 24-hour SO₂ concentrations are associated with moderate to strong persistent winds from the south-southwest. On the other hand, the highest 3-hour and 24-hour SO₂ concentrations in the upper portion of the Ohio Valley are often associated with a large, slow moving high pressure system. In this case, the SO₂ emitted overnight is trapped and then brought to the ground at midday in response to the heating of the ground surface. An example of this sharp midday peak of SO₂ is shown in Figure 6 for several monitors at the AEP Muskingum Plant. If the 25 episode dates for each network are examined, there appear days or groups of days on which more than one network reports an episode. This clustering of episode dates can extend an entire month as was the case in October 1974 and January 1977. The 24-hour SO₂ concentrations during these periods were some of the highest of the 25 selected for each network. This phenomenon is due to the extent



FIGURE 5—Map of the AEP network locations showing second highest 3-hour SO_2 concentrations ($\mu g/m^3$) for 1976

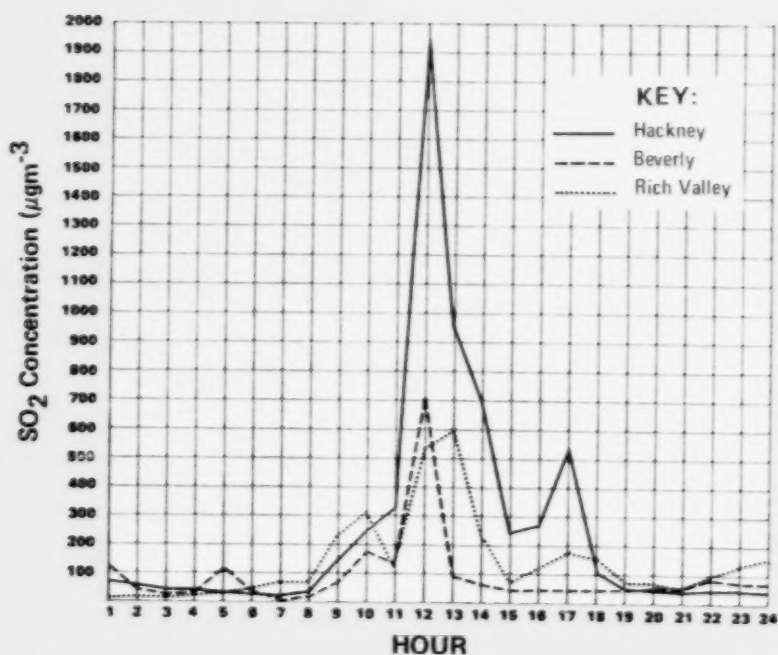


FIGURE 6—Diurnal variation of SO_2 concentrations at the Hackney, Beverly and Rich Valley sites of the Muskingum network on April 14, 1976

and movement of synoptic scale features and their associated worst case meteorological conditions across the region. In some cases, not only do the critical meteorological conditions extend over more than one network, but actual regional scale transport of SO_2 can occur. This appears to have been the case during January 1977 when plume trapping and recirculation occurred with the frequent passage of cold high pressure systems.

VARIATION IN DISPERSION METEOROLOGY

The variation in dispersion meteorology from one year to the next is illustrated in Figure 7, which shows substantially fewer monitoring network SO_2 episodes during January 1976 than January 1977. The first implication of this result is the difficulty in the assignment of a base year concentration for 3-hour and 24-hour averaging times. A more important implication is that any program designed to examine the validity of a particular dispersion modeling technique must involve an analysis of several years of monitoring data. Only in this case can one be assured that a reasonable fraction of the worst-case meteorological conditions have been examined.

EVALUATION OF POINT SOURCE MODELS

In light of this extended record of air quality and meteorological data at each of the network sites, the EPA Office of Air Quality Planning and Standards and the Meteorology and Assessment Division are making use of this data base for the evaluation of the point source regulatory models which were described earlier. An important aspect to this evaluation is the comparison of the meteorological conditions for the

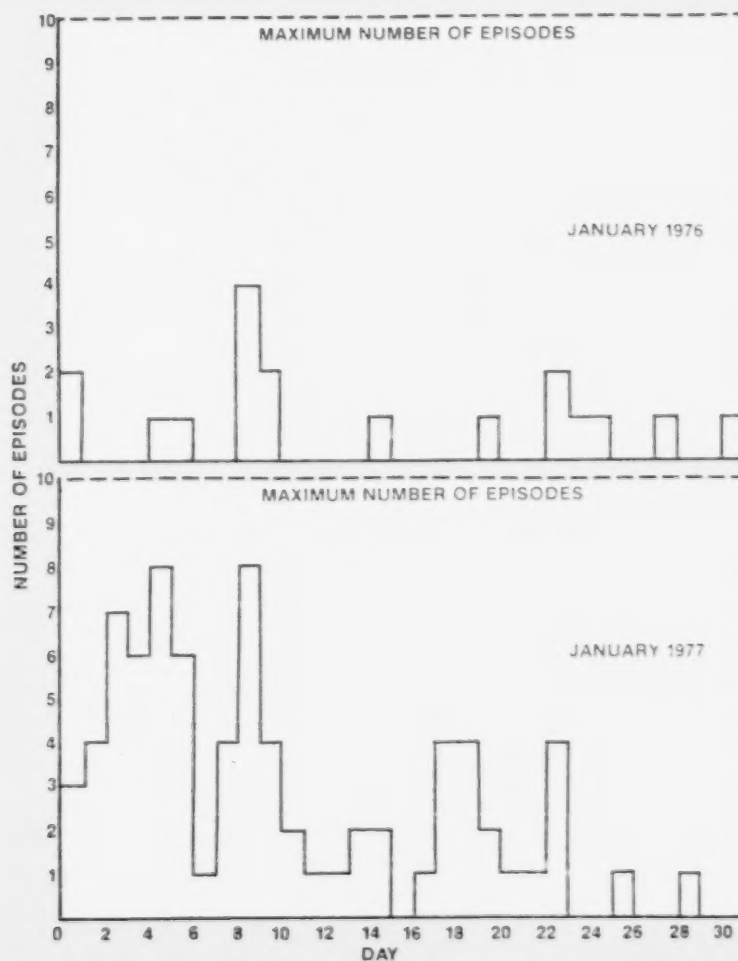


FIGURE 7—Number of AEP network SO_2 24-hour episodes during January of 1976 and 1977. The episode days are selected on the basis of the highest 25 daily SO_2 concentrations observed for each network-year.

observed and calculated 25 highest 3-hour and 24-hour concentrations. For the periods of the highest observed concentrations, a case by case comparison of observations and model calculations will be carried out. While an actual quantitative comparison of observed and calculated hourly concentrations is difficult because of the uncertainty of the actual plume centerline location, it will be evident whether the model could have possibly described the event. Of special interest will be the evaluation of the calculated A-Stability impacts mentioned earlier in connection with the discussion of air quality constraints and standardized point source models. Our analysis to date has identified a number of daytime light wind 3-hour SO_2 episodes similar to the one shown in Figure 6, but the concentration peak extends over a much wider area and to a greater distance from the plant than would be calculated by use of the A-Stability vertical dispersion curve. If the evaluation study identifies this observed light wind 3-hour impact as critical for elevated point sources, this implies that additive short-term impacts would be an important factor in the PSD analysis.

EPISODE ANALYSIS

This treatment of air pollution episodes has been extended to other portions of the ORBES Aerometric Data Base to obtain a better understanding of regional pollutant transport and transformation characteristics during periods of observed high concentrations. This episode analysis has been conducted principally with sulfate, ozone, and TSP data from the National Aerometric Data Branch. Whenever possible, these data have been supplemented with measurements from the Sulfate Regional Experiment (4) and the Tennessee Valley Authority. For each pollutant and year, the data were screened to find for each day the number of monitoring locations reporting a concentration greater than a specified threshold value and the total number of monitors reporting on that day. In spite of the every-6-day sampling schedule for sulfate, this has proved to be a reliable way for the identification of episodes. Since these episodes take several days to develop, the probability of missing an episode is smaller than would be indicated by the once-every-6-day coverage. A selection of ozone episodes is performed by means of a similar threshold analysis of 1 p.m. ozone concentrations.

The most striking result from this analysis is the simultaneous occurrence of sulfate and ozone episodes. One such case is shown in Figure 8, which is based on

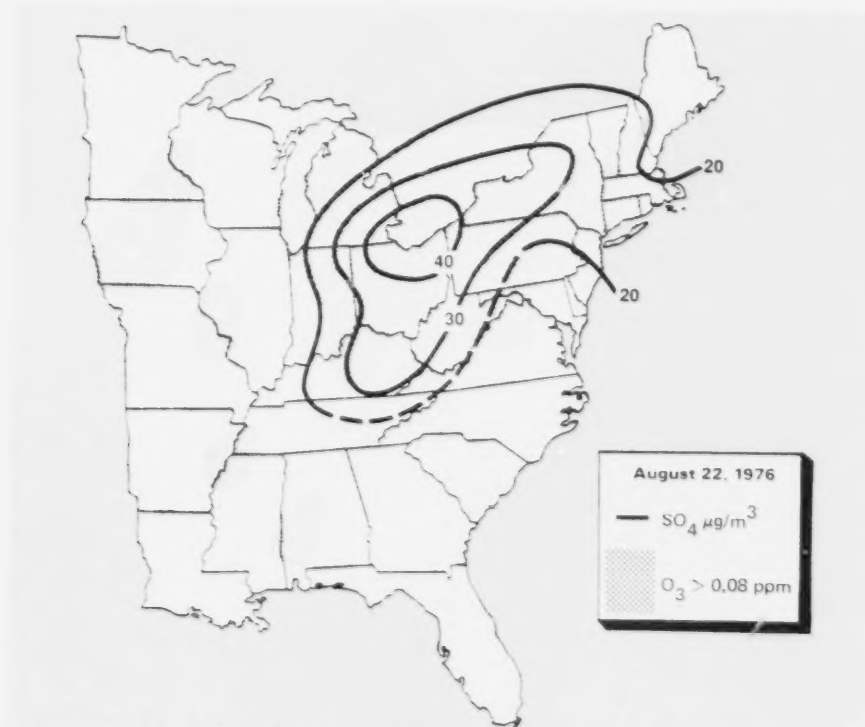


FIGURE 8—Spatial distribution of sulfate and ozone for August 22, 1976

SIMULTANEOUS OCCURRENCE OF EPISODES

average sulfate and ozone concentrations for each Air Quality Control Region (5). The August 22, 1976, case is an interesting episode because it shows a recirculation of pollutants within a relatively small region of eastern Ohio and western Pennsylvania. This recirculation is indicated by the air parcel trajectories shown in Figure 9. During August 21 and 22, there was no significant movement of the high pressure center just south of Lake Erie. In fact, the entire eastern United States was dominated by high pressure with a weak gradient. The ozone episode began on August 18 with 38 of the monitoring stations exceeding the 0.08-ppm level. This number grew to reach a peak of 117 monitors exceeding this level on August 21 and then declined to 99 on the following day. This was also a period of reduced visibility throughout the midwest and northeast. The enhanced satellite photograph (see Figure 10) made available by Dr. Walter Lyons shows the extent of the haze layer on this day. The haze shown in this photograph is most likely due to the presence of fine particulates which, in large measure, are produced by the conversion of tall stack sulfur dioxide emissions to sulfate.

In addition to the recirculation condition, another typical summertime sulfate episode has been found from an analysis of the data. This episode is characterized by persistent southwesterly winds in advance of an approaching cold front. The pattern of

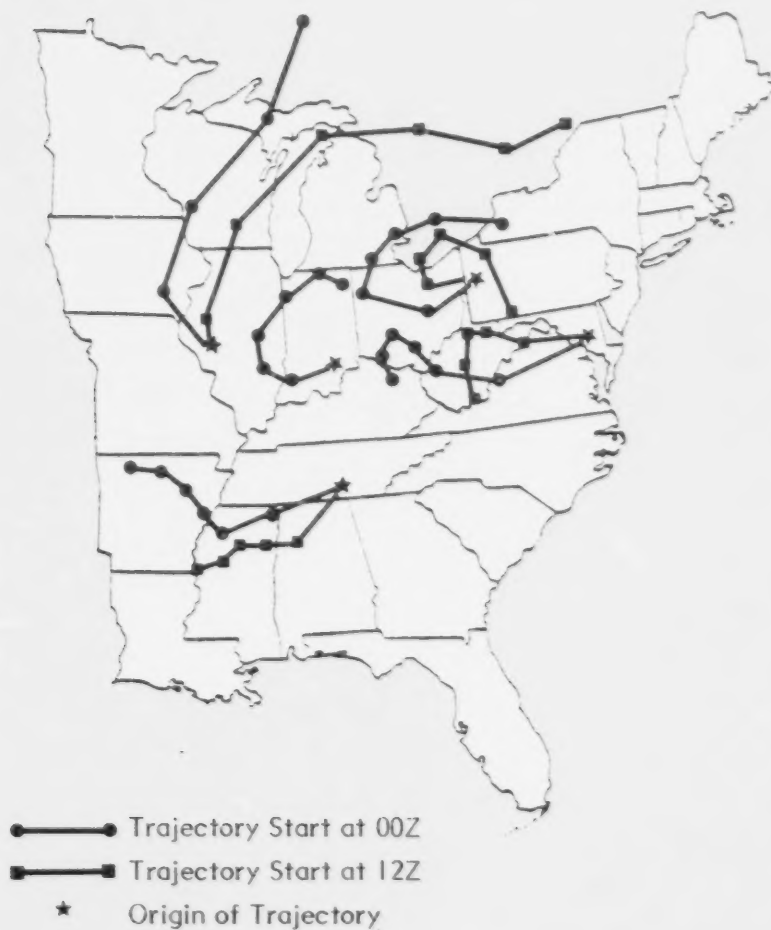


FIGURE 9—Forward running air parcel trajectories (600-meter level) beginning August 20, 1976. Interval between trajectory points is 12 hours.

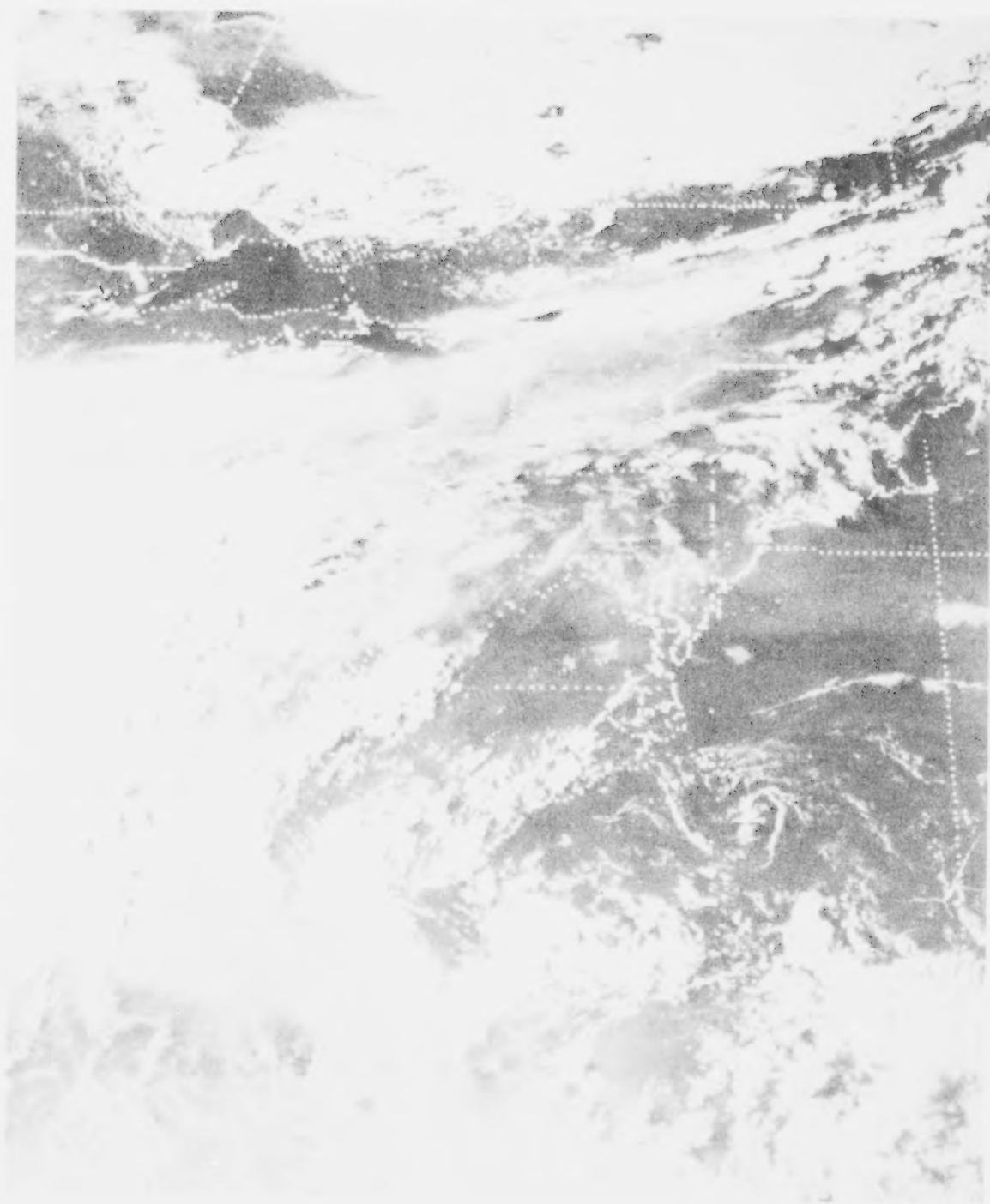


FIGURE 10—Satellite photo for August 22, 1976, showing the haze layer over the midwest and northeast

sulfate concentrations for August 27, 1974 (see Figure 11) is an example of one of these persistent wind episodes. The highest sulfate concentrations during this period were confined to the warm sector of an eastward moving occluded frontal system.

LOCAL AND REGIONAL ANALYSES

These analyses of local and regional air quality data have provided much more useful information than would have been gained through the routine application of existing models. In the first place, the data analysis gave a picture of existing air quality throughout the ORBES region. Moreover, it has made possible the identification of critical meteorological conditions for elevated pollutant concentrations. An understanding of the meteorological conditions associated with air pollution episodes is essential since many of the air quality standards and allowable increments are expressed in terms of concentrations which may be exceeded only once per year. Damage to vegetation is a strong function of the peak SO_2 and ozone concentrations during the summer months. Unfortunately, most of the existing air quality models have not been designed to specifically deal with these episodes, but instead incorporate detailed algorithms for the description of all possible conditions. Without first understanding the worst-case meteorological conditions from an analysis of ambient data, a modeler could devote years of effort to the development of a detailed model which could be of little use for the calculation of concentrations under the actual critical conditions. Another benefit from the analysis of air quality and meteorological data is the finding that simpler modeling approaches can be used, so that computing and input data

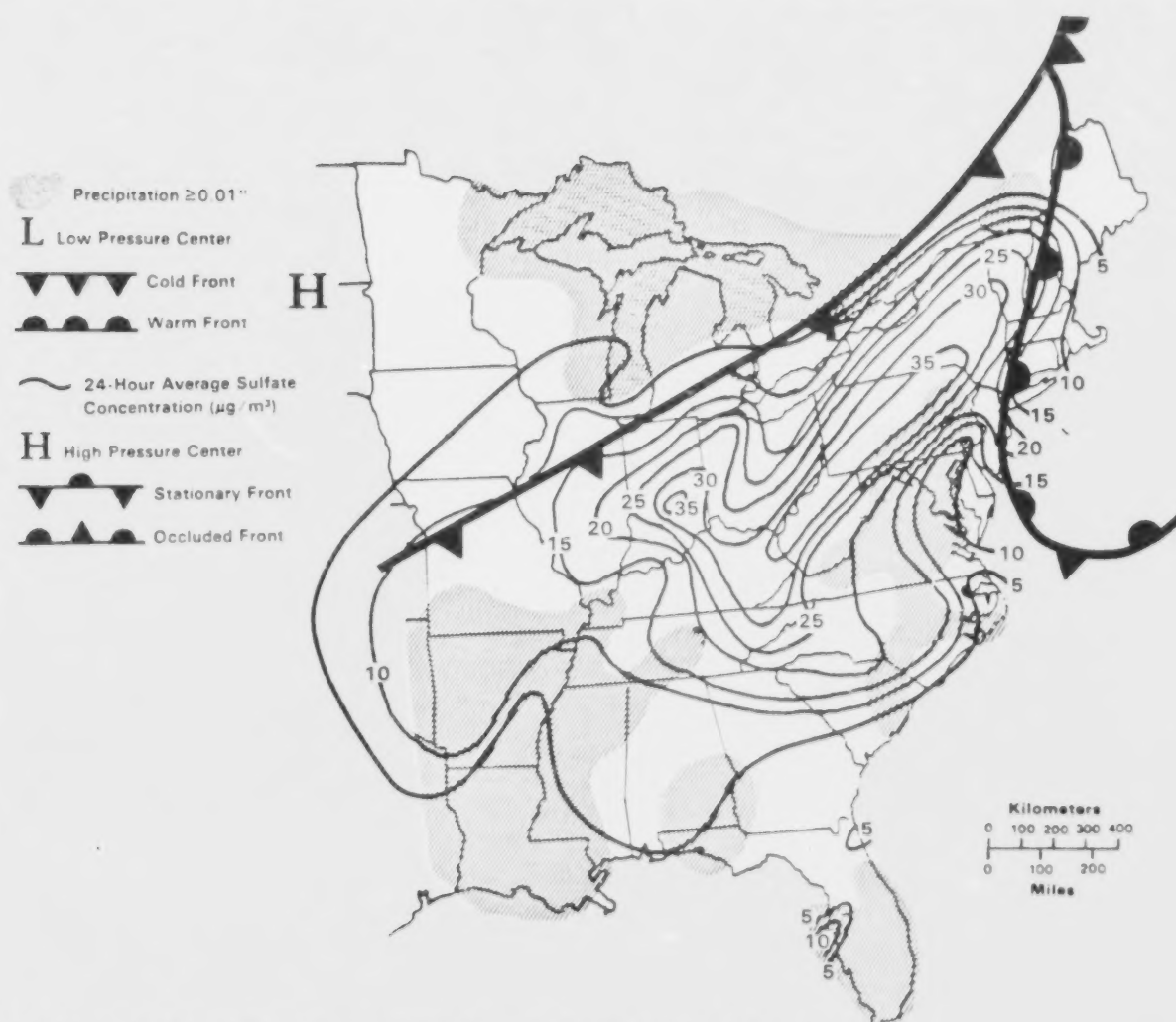


FIGURE 11—Isopleths of sulfate concentrations and synoptic weather patterns for August 27, 1974

MODELING APPROACH DEVELOPED

requirements will not be prohibitive for the user. These simpler modeling approaches may actually yield more accurate results than the more complex models. For example, detailed calculations of primary pollutant concentrations for an urban area are often no more accurate than those obtained from a very simple area source model. This result can occur since, for most air pollution problems, there are generally only a few factors of major importance and if these are described properly, the model calculations will be reasonable. The inclusion of further complexity in a model, unless warranted by an analysis of available data, may introduce a large component of unwanted noise into the model predictions.

Based on the analysis of these air pollution episodes, a modeling approach has been developed for the evaluation of air quality impacts for various energy growth scenarios. Short-range pollutant impacts are based on the results from standardized Gaussian models, modified to reflect the influence of observed critical meteorological conditions. Since pollutant transport plays a crucial role in the occurrence of the worst regional sulfate episodes, a regional model has been selected which employs a very efficient, yet accurate, algorithm for the calculation of pollutant advection and diffusion (6). The model also allows for the time-dependent transformation of SO_2 to sulfate and the removal of both chemical species by dry and wet deposition. The computational efficiency of this model allows its evaluation for a large number of episode cases and its application to develop regional source-receptor relationships. Model calculations of regional sulfate concentrations for the August 27, 1974 episode are shown in Figure 12. A large fraction of the sulfate observed in the Upper Ohio Valley on this day can be traced to SO_2 emissions in the lower part of the valley (7). During a light wind stagnation condition similar to the August 22, 1976 episode, however, emissions in the Upper Ohio Valley can actually be transported as sulfates down the valley. Regional model calculations are currently being carried out for additional episode cases to estimate the change in regional SO_2 and sulfate concentrations for several ORBES energy growth scenarios under different governmental regulatory policies and future power-plant siting patterns in the Ohio River Basin.



FIGURE 12—Sulfate levels ($\mu\text{g}/\text{m}^3$) predicted by the regional sulfate model for August 27, 1974

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questions & answers

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American Medical Association

Benjamin Linsky, P.E.
West Virginia University

QUESTION

For years physicians have looked at effects of influenza in terms of excess mortality. Are there any current plans to look at the spectacular air pollution effects which we have just seen documented in terms of excess mortality in the areas covered by those systems of pollutants?

RESPONSE: Dr. William Wilson (EPA)

There are no fully developed plans, but there are discussions among health effects people about the possibility of bringing in mobile health effects units to look for more subtle effects of pollution in relationship to these episodes. I do not think anyone has suggested looking for excess mortality, but that would be simpler than taking the vans in and looking for changes in respiratory function.

COMMENT

There is a study done by the West Virginia Department of Natural Resources which found streams that had been fishable and stockable have become unfishable and unstockable because of acid rain. I hope the author will put the report into the peer review literature.

QUESTION

The visibility limitation at Lake Tahoe is set at 20 miles, specifically so people can see across the lake. Is this sort of criterion valid when used by state and local governments in setting minimum visibility limitations?

RESPONSE: Dr. Wilson

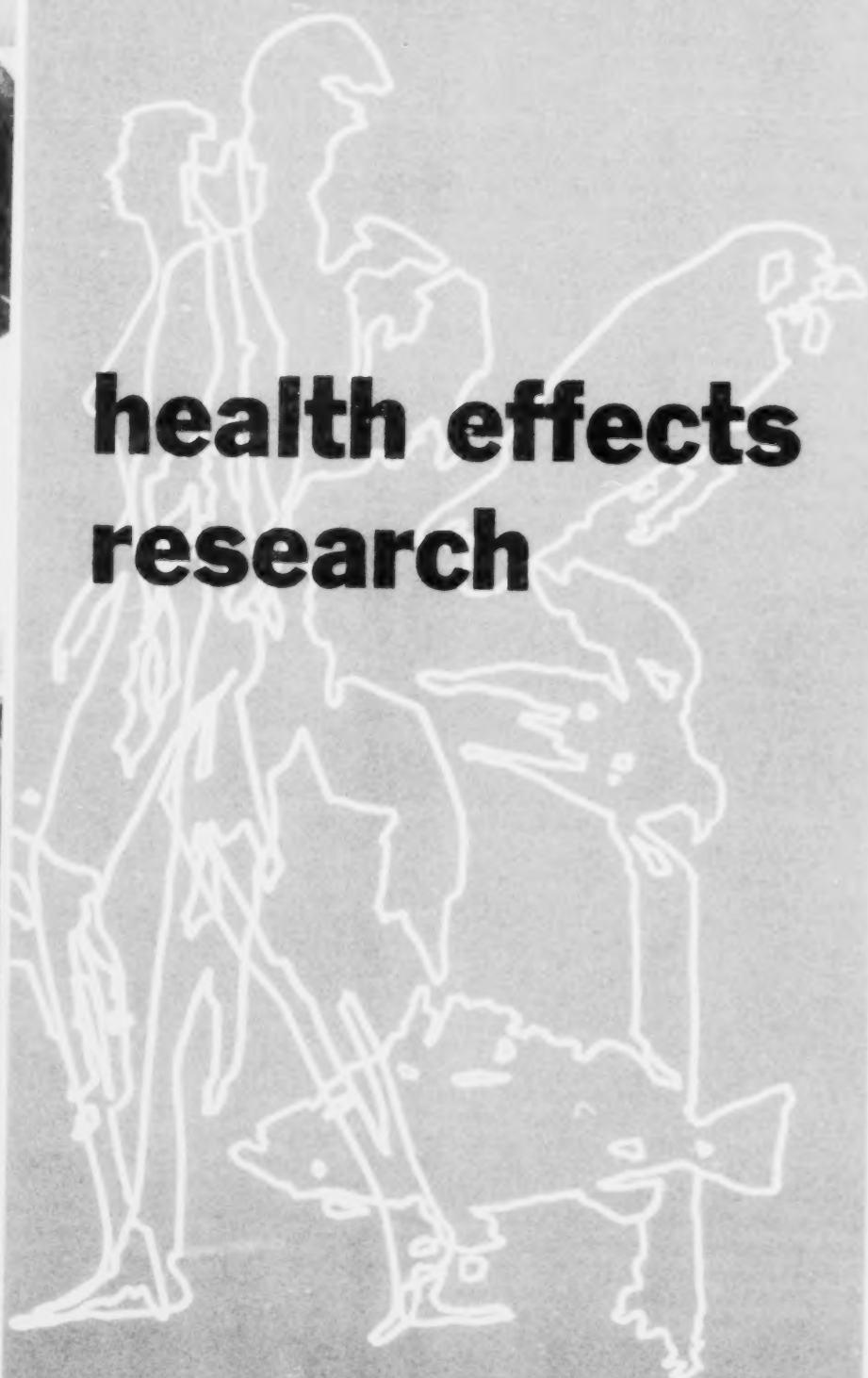
Different standards are needed for different parts of the country, depending on what objects you want to see and how badly you want to see them. The people of New Mexico maintain that if you cannot see the mountains in New Mexico, why live there? Visibility certainly is a

consideration in terms of property values. Another important thing to consider is that if you want to see something 20 miles away you may have to set your standard in terms of a visibility distance of more like 100 miles, a fact probably not realized at the time of the Lake Tahoe studies. There is a difference between visibility distance and visual air quality. Local agencies will have to consider this in setting standards for their emission sources. They will have to consider as well that their emission sources not only impact them locally but affect other areas.



session 6

health effects research





J. Michael Holland

ASSESSMENT OF THE CARCINOGENIC RISK FROM ENERGY-RELATED ORGANICS

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UNKNOWN-REFERENCE DOSAGE COMPARISON

The extraction, refining, and use of natural petroleum over the last half century have resulted in extensive industry experience with these materials. Based upon this experience, there is justifiable confidence in the adequacy of current procedures to limit occupational dermatoses and skin cancer arising from contact with natural petroleum and distillate fractions. This, in part, may result from the fact that natural petroleums possess a low order of intrinsic carcinogenicity (1). By contrast, it is well documented that coal liquids and shale oils are human skin carcinogens, under conditions of prolonged or unregulated exposure (2-4). Given the inevitable need for massive quantities of these materials it is essential that their potential for skin contact toxicity and carcinogenicity be assessed. There is an additional question concerning whether the greater skin carcinogenic potency manifest by syncrudes will be reflected in finished products that may eventually enter commerce.

To facilitate risk-benefit decisions our approach has been to obtain comparative and quantitative data concerning the skin carcinogenicity of syncrudes, derived from various starting materials and by different processes relative to both natural petroleum and the pure reference carcinogen, benzo(a)pyrene (BP). To quantitate the response, we have adapted biostatistical methods that have been used for the comparative bioassay of tobacco smoke condensates (5). Using these approaches, it eventually will be possible to relate the dose response obtained for a specific syncrude to that obtained for BP. By comparing the dosages, between unknown and the reference, re-

quired to elicit a common risk or probability for skin cancer, we can accurately and reproducibly compare different materials, as well as assess the importance of various bioassay conditions (6).

TEST MATERIALS

Materials examined by us have been obtained from a variety of small scale process simulations or process development units. For this reason the findings may or may not be relevant to larger scale or commercial processes that utilize similar source material. The question concerning whether these data reflect a trend or reveal characteristics applicable to broad classes of generically related crude liquids is still the subject of ongoing experimentation. Our primary use of these materials, to date, has been to establish appropriate bioassay conditions for reliable, and potentially extrapolatable, analysis of the skin carcinogenicity of generically similar materials. It is anticipated that this knowledge and experience will facilitate analysis of materials that may some day be produced commercially. Table 1 summarizes information concerning the general characteristics of the test materials. Additional detail concerning their chemical and physical characteristics has been published elsewhere (7,8).

SKIN CARCINOGENICITY

Materials have been tested for carcinogenic activity by diluting them in a heterogeneous solvent. The solvent consisted, by volume, of 30% acetone and 70% cyclohexane. This mixture was selected because it would permit solution or uniform dispersal of all the test materials. Test solutions were made fresh weekly and applied, using a 50 microliter automatic pipette. Equal numbers of male and female C3Hf/He inbred mice, 10 weeks old at the start of each experiment, were used. Details concerning experimental animals and procedures can be found elsewhere (6,9).

Data are presented for two separate experiments. The first study involved 3 times weekly (Monday, Wednesday, Friday) application of a 50% (w/v) concentration of the various syncrudes as well as the composite natural petroleum to groups of 30 mice for 20 weeks. Following this exposure, the mice were held for an additional 20 weeks to allow expression of skin lesions, in the absence of continued application of the test materials. The total period of observation of these animals was approximately 300 days. In the second experiment, groups of 20 mice were exposed to serial dilutions of

TABLE 1
Characteristics of materials tested for skin carcinogenicity

Material	Type	Specific Gravity	Wt. % Sulfur	Viscosity (Sec. 100°F)	Pour Point (°F)	Color	Wt. % Nitrogen
Wilmington, California*	Natural	0.938	1.59	470	< 5	Brownish Black	0.631
South Swan Hills, Alberta, Canada*	Natural	0.826	0.11	37	< 5	Brownish Green	0.056
Prudhoe Bay, Alaska*	Natural	0.893	0.82	84	15	Brownish Black	0.230
Gach Seran, Iran*	Natural	0.880	1.57	72	< 5	Brownish Black	0.226
Louisiana-Mississippi Sweet†	Natural	0.825	0.17	50	< 5	Brownish Green	0.067
Arabian Light†	Natural	0.858	1.80	46	< 30	Brownish Black	0.1-0.2
Shale Oil‡	Centrifuged crude product	0.909	0.93	66	30	Brownish Black	1.14
Coed Syncrude	Hydrotreated product oil	0.940	0.05	48	43	Pale Yellow	0.05
Synthoil Syncrude	Centrifuged crude product	1.136	0.52	80(180°F)	—	Brownish Black	1.30

* Bureau mines routine crude oil analysis. Data provided by J. Dooley, Bartlesville Energy Technology Center, Bartlesville, Oklahoma.

† Analysis not based on these specific samples and therefore the data are approximate and given for comparison purposes only: provided by J. Dooley.

‡ Laramie Energy Technology Center, Run No. 14, Colorado Shale, Rifle, Colorado. Fisher assay 24.4 gallons/ton from a 150 ton above ground simulated *in situ* retort. Data provided by John McKay.

the same materials, starting at 50%. Exposure was twice weekly (Monday and Thursday) for 30 weeks followed by a 20-week expression period. The total observation period of these animals was approximately 350 days. Taken together, the two experiments allow a comparison of the materials as a function of temporal aspects of exposure. In both experiments, animals received 60 exposures. However, in the first study the 60 doses were applied in 20 weeks, but in the second, 30 weeks were required.

TEST RESULTS

The results, expressed in terms of grossly typical squamous carcinoma, are listed in Table 2 for the 3/wk-20 week exposure and in Table 3 for the 2/wk-30 week exposure. Under both treatment conditions, the syncrudes were found to be efficient skin carcinogens while natural petroleum failed to induce skin cancer. In the 20-week study, both synthoil and shale oil were more active than COED, with synthoil exhibiting a slightly greater activity than with shale oil. This pattern was duplicated in the 30 week study with the order of carcinogenic activity, synthoil>shale oil>COED>>natural petroleum. Natural petroleum, while negative under these experimental conditions, does possess a low order of carcinogenicity. In other experiments in

TABLE 2

Epidermal carcinogenicity of fossil liquids following 3 times weekly skin application for 20 weeks at a 50% concentration

Material	Percent of Mice With Squamous Carcinoma	Average Latency (Days±SE)	Percent Mortality
Synthoil	63	153 ± 8	20
Coed	37	192 ± 13	3
Shale Oil	47	151 ± 14	37
Petroleum Blend	0	—	0

TABLE 3

Epidermal carcinogenicity of fossil liquids following 2 times weekly skin application for 30 weeks at various concentrations

Material	Percent (W/V) Concentration	Percent of Mice With Squamous Carcinoma	Average Latency	Percent Mortality
Synthoil ¹	50	80	214±11	45
	25	35	238±22	5
	12	10	287±50	5
	6	0	—	0
Coed	50	10	329±17	0
	25	5	253	0
	12	0	—	0
	6	0	—	0
Shale Oil	50	35	208±9	30
	25	5	213	0
	12	0	—	0
	6	0	—	0
Wilmington Petroleum	50	0	—	0
	25	0	—	0
	12	0	—	0
	6	0	—	0

INCREASED INTERVAL DECREASED RATE

which a 0.2% concentration of the composite petroleum was applied 3 times weekly for 24 months, an 8% final incidence of squamous carcinoma was obtained with an average latency of 658 ± 22 days (10).

The temporal distribution of tumor latencies is illustrated in Figure 1 for the 20 and 30 week data, respectively. These curves reveal that, in general, increasing the inter-treatment interval from 56 (3/wk) to 84 (2/wk) hours is accompanied by a longer average latency and decreased skin cancer frequency particularly with COED, but also evident for shale oil. Interestingly, while skin tumors developed at later times, the cumulative incidence was actually greater when mice were exposed to synthoil at a reduced dose rate. This suggests that synthoil is less subject to a decreased carcinogenic effect as a result of an increased interval between successive exposures.

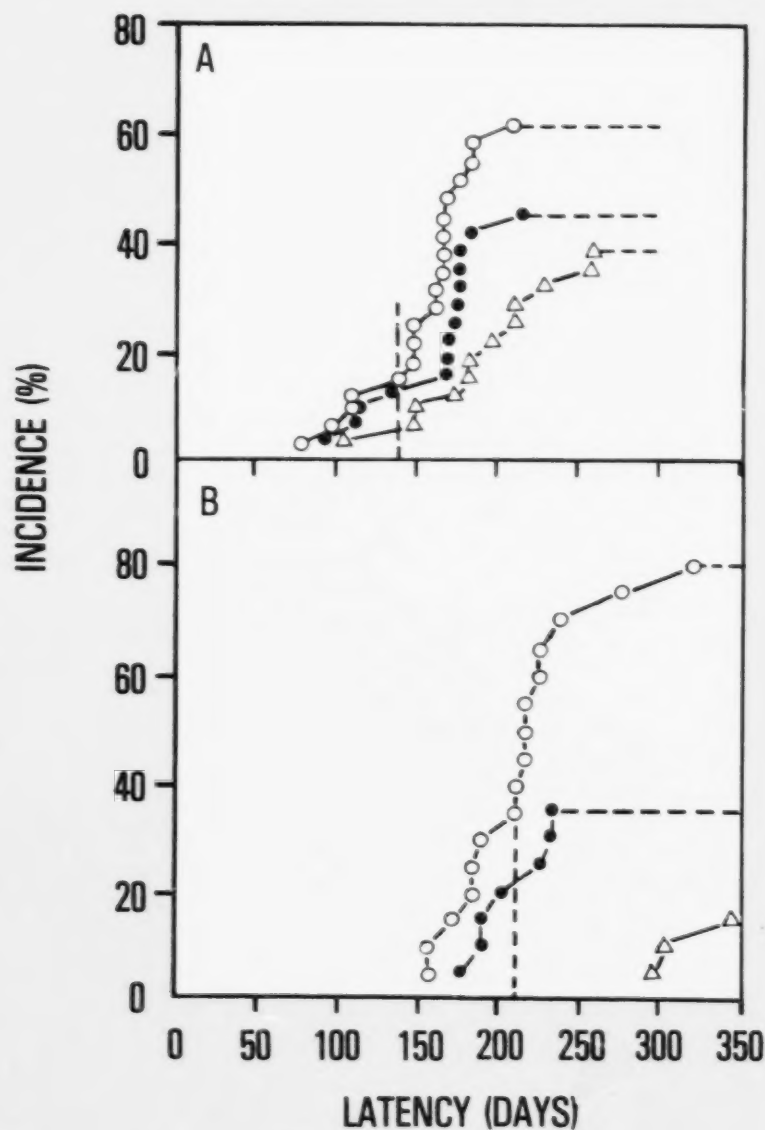


FIGURE 1—A Incidence of squamous carcinoma included by three times weekly application of 50% solutions of synthoil (O), shale oil (●) or coed (Δ) syncrudes for 20 weeks. **B** Incidence of squamous carcinoma induced by two times weekly application of 50% solutions of synthoil, shale oil, or COED (same symbols), for 30 weeks.

DIFFERENCES AMONG MATERIALS

The difference among the various materials are more clearly illustrated in Table 4, which contrasts the average time to occurrence of skin cancer as well as final incidence in the two experiments.

TABLE 4

The effect of dose rate on cumulative incidence and average latency of skin cancer induction by syncrudes

Material	Intertreatment Interval (Hrs)	% Incidence	Average Latency ($\pm$ SE)	Dose Rate Effect Upon Tumor Expression
Synthoil	56	63	153 $\pm$ 8	Enhanced Expression
	84	80	214 $\pm$ 11	
Coed	56	37	192 $\pm$ 13	Reduced Expression
	84	10	329 $\pm$ 17	
Shale Oil	56	47	151 $\pm$ 14	Reduced Expression
	84	35	208 $\pm$ 9	

RELATIVE POTENCY

Relative potency is a reproducible, quantitative, and extrapolatable means to compare the skin carcinogenicity of any two materials, if each is applied under identical conditions to genetically homologous test animals. The approach we have taken previously to establish the carcinogenic potency of a material has been to compare the dose responses obtained for the test material with that obtained for reference skin carcinogen, BP (6). Proportions of mice surviving over the duration of the study, without skin tumor, are fitted to a three parameter Weibull distribution by the maximum likelihood method. Dose responses, in terms of the model, for the unknown compound or mixture and the reference carcinogen, are then compared by relating doses of the unknown, relative to BP, that would be required to elicit a common probability of skin cancer. This allows a quantitative estimate of the degree of difference between the two materials. This approach will enable us to reproducibly compare different materials tested under standard conditions at different times. In addition it will facilitate interspecies comparison because the reference carcinogen used is a component of man's environment. As such, estimates of human population exposure to BP will inevitably improve and with each improvement will come better appreciation of the extent, if any, of adverse health impact attributable to observed differences in BP exposure. With this common link between the two species, known BP dose responses, then extrapolation of this to other hydrocarbon skin carcinogens will be facilitated.

For purposes of the present communication, data concerning the response of C3H mice to topical application of BP in the same acetone-cyclohexane solvent, has been summarized in Table 5. BP was applied at concentrations ranging from 0.1% to 0.004% which are much lower than were used for any of the fossil liquids, but on the

TABLE 5

Skin cancer induction by Benzo(A)pyrene applied three times weekly*

Percent Concentration (Wt/Vol)	Percent of Mice with Squamous Carcinoma*	Average Latency†
0.1	100	139(4)
0.02	100	206(7)
0.004	90	533(5)

* Duration of exposure at lowest dose was 24 months.

† Days $\pm$ standard error.

FLUORESCENCE MICROPHOTOMETRY

same 3-times-weekly schedule. The concentration of BP that came closest to yielding an average tumor latency equal to that of synthoil was somewhat less than 0.1%. Thus a 0.1% solution of BP is approximately equipotent to a 50% solution of synthoil, all other conditions being equal. A crude estimate of relative potency can be obtained from this relationship by expressing potency as a ratio of these two percentage concentrations which in this case is 500. Therefore, as a first approximation, it would appear that synthoil is 500 times less active a skin carcinogen than BP. This estimate is preliminary and subject to refinement as the full dose response relationship, for both the test material and the reference carcinogen, is taken into account.

To better understand the basis for the difference in carcinogenicity observed among the syncrudes, we have developed analytical methods to observe and quantitate the movement and localization of syncrudes in the skin (9). At various times after standardized skin application, frozen sections are obtained and the distribution of syncrude is determined by fluorescence microphotometry. All fossil liquids thus far examined are highly fluorescent and thus this measure provides a convenient marker for observing skin distribution. It also should be kept in mind that polyaromatic hydrocarbons, known to be a carcinogenic component of fossil liquids, are also highly fluorescent and that this feature was exploited in their isolation and identification (11).

Using this approach we have compared the intensity and distribution of skin fluorescence for each of the syncrudes as well as the composite petroleum. The data in Table 6 indicate the observed fluorescence intensity (in arbitrary units) at specific locations. Solution of each material was adjusted to contain 2 mg solids per ml. One hundred microliters of this solution was applied, using a micropipette being careful to ensure as uniform a dispersal as possible. Using dye solutions, it was independently established that this volume of an acetone-cyclohexane solvent will reproducibly cover an area approximately 100 cm². From this relationship, we estimate the area concentration to have been 200 µg/cm².

TABLE 6
Distribution of fluorescence following topical application of petroleum liquids

Site of Measurement	Time After Application	Average Fluorescence Intensity *			
		Synthoil	Coed	Shale Oil	Composite Crude
Skin Surface	1 hr	185 (32)	75 (11)	49 (14)	65 (11)
	4 hr	219 (58)	87 (11)	37 (5)	70 (15)
	24 hr	107 (26)	98 (13)	42 (8)	52 (22)
	8 days	70 (25)	40 (10)	31 (2)	28 (2)
	14 days	37 (7)	28 (6)	25 (2)	25 (1)
Sebaceous Gland	1 hr	540 (123)	172 (49)	70 (21)	137 (44)
	4 hr	422 (101)	185 (61)	66 (12)	140 (88)
	24 hr	454 (114)	190 (24)	109 (21)	135 (40)
	8 days	112 (21)	43 (6)	29 (1)	27 (1)
	14 days	42 (11)	23 (1)	25 (1)	25 (1)
Papillary Dermis	1 hr	28 (2)	29 (2)	20 (1)	26 (2)
	4 hr	28 (2)	29 (2)	24 (1)	24 (1)
	24 hr	27 (2)	29 (3)	24 (1)	26 (1)
	8 days	27 (1)	27 (2)	24 (1)	25 (1)
	14 days	25 (1)	25 (1)	25 (1)	25 (1)

*Arbitrary fluorescence units ± standard error. Tissue background in mice treated with solvent only was approximately 25 units.

FLUORESCENCE INTENSITY

Fluorescence intensity was determined at specific sites within frozen sectioned skin, at fixed times. Concentration of fluorescent material was observed to occur in sebaceous glands. Fluorescence intensity was greatest with synthoil and least for COED at all times. The degree of initial fluorescence was also positively correlated with the speed of clearance. It is interesting to note that fluorescence significantly above dermal background was detectable in the sebaceous glands of mice, for up to 14 days following a single skin application of synthoil. Thus synthoil exhibited a high affinity for skin lipid while the other materials were cleared rapidly. It may be significant that the effect of increasing the interval between successive exposures was less pronounced for synthoil than with the other compounds. One possible explanation for this may well have been that synthoil persists in skin longer than the other materials and thus there is a less pronounced effect introduced by increasing the interval between successive exposures.

MOUSE SKIN CARCINOGENESIS DATA

The value and relevance of animal carcinogenesis bioassay data could be increased significantly if a means could be found to directly compare the responsiveness of human skin and experimental animal skin to the same test materials under identical *in vivo* conditions. We feel that it may be feasible to do this using the genetically athymic nude mouse (12). This animal is incapable of recognizing and thus rejecting foreign tissue grafts. We have established a pathogen-free colony of these mice under conditions which maximize experimental flexibility. We have further determined that it is feasible to establish xenografts of human skin for periods sufficiently long (up to 300 days) to easily compare more potent skin carcinogens. The essential microscopic differences between mouse skin and human skin as well as an illustration of the graft procedure are given in Figure 2. Panel A is a microscopic section of mouse skin

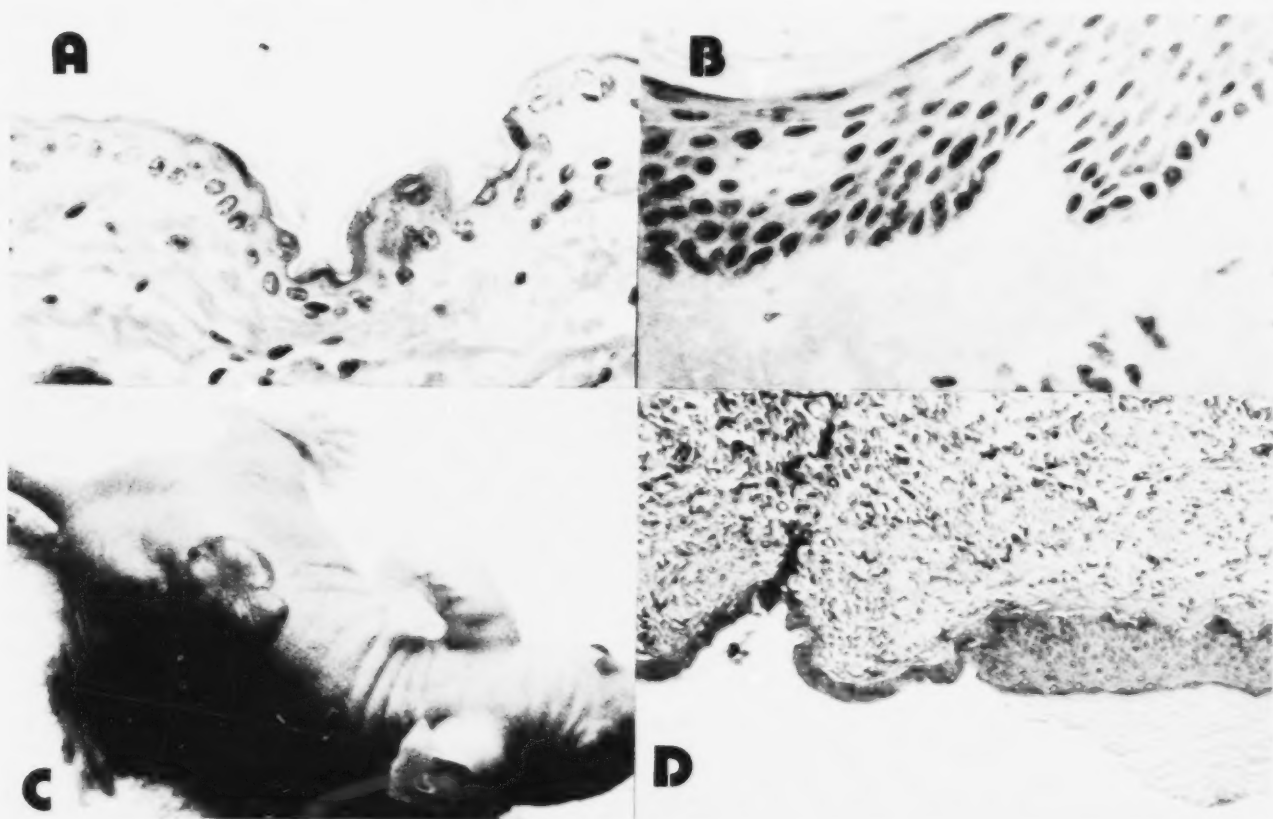


FIGURE 2—A Light microscope section of mouse skin revealing a thin cellular epidermis. B Similar section of human skin revealing a thicker, more cellular epidermis. C Human skin grafted to the back of an athymic nude mouse. Healing is complete with no overt evidence of inflammation. D Microscopic section of human skin graft. The margin of the graft (arrow) reveals an abrupt transition from epidermis characteristically human to that characteristic of the nude mouse.

revealing a characteristic of this species, an exceedingly thin epidermis. Panel B is a similar section of human skin depicting a more highly cellular and physically less permeable epidermis. Panel C is a gross photograph of an athymic nude mouse bearing a well established graft of human skin. The human skin graft is easily distinguished because the host mouse is albino and human skin is pigmented. Evidence that these grafts are well tolerated by athymic mice, without evidence of rejection, is revealed in panel D. This is a microscopic section of a skin graft like that displayed in panel C, which reveals that the thicker epidermis characteristic of human skin is preserved and that mouse and human epidermis merge without a noticeable interruption.

These findings, while still preliminary, are encouraging because they point a way to achieve the goal mentioned previously. If a sufficient number of these grafts can be established to allow direct application of reference carcinogen solutions, then it should be possible to compare the biological response of human skin to chemical and physical agents, singly and in combination, and to compare directly differences in tissue and cellular and molecular aspects of the response across species lines. To control the possible interference introduced by the graft procedure itself due to alteration of nerve supply and microvasculature, control grafts of animal skin of known carcinogen susceptibility can be tested in parallel with the human skin. Any difference in latency, histogenesis, or biological behavior of tumors induced in the graft versus those induced in the same tissue on its natural host could then be assumed to be constant regardless of species and thus factored into the interpretation of the data.

SUMMARY AND CONCLUSIONS

We have determined that three synthetically-derived fossil liquids are more potent skin carcinogens than natural petroleum. None of the syncrudes approached the specific carcinogenicity of a reference carcinogenic hydrocarbon, benzo(a)pyrene (BP). By comparison of the dose rates necessary to achieve similar average tumor latencies, under identical experimental conditions, it was estimated that synthoil had a mouse skin carcinogenicity one five hundredth that of pure BP.

Increasing the interval between successive exposures, while keeping the total number of exposures constant, had the effect of decreasing risk of skin cancer for both shale oil and COED but not for synthoil. The percent of mice developing skin cancer with the latter material actually increased as the dose rate was reduced from three to two exposures per week. We interpret this as an indication that high dose rate application of synthoil may actually inhibit either skin cancer induction or expression, probably as a result of toxic components present in the whole material. As the dose rate is decreased, there is sufficient time between successive exposures for the skin to eliminate or recover from the toxic but not the carcinogenic effect and thus expression of neoplastically transformed epithelial cells is enhanced. Another factor that also may contribute to a diminished dose rate effect is the slower skin clearance of synthoil relative to any of the other materials tested. Based upon fluorescence intensity as a measure of the quantity of material trapped in sebaceous glands, synthoil components were detected in sebaceous glands for up to 2 weeks following a single surface application of synthoil while all other materials were observed to clear within 1 week. Therefore the question of whether workers who are exposed only infrequently or accidentally are at as great a risk as those who are exposed continuously could depend upon how rapidly the material is cleared from the skin. For syncrudes similar to the present shale oil and COED, detoxification and skin clearance would be expected to be rapid and therefore increasing the interval between exposures would be anticipated to result in a decreased tumor risk. For materials with the skin clearance characteristics of synthoil even infrequent exposure could pose a significant risk.

MORE MODELS NEEDED

Future biological research in support of the synthetic fuels industry needs to emphasize the potential applicability of animal carcinogenesis data to the question of human risk. More comprehensive and relevant experimental models need to be developed and evaluated for the purpose of risk *quantitation*. There is an additional need to better understand the biological interactions between the target tissue and the whole chemical mixture. We have explored the feasibility of using the athymic nude mouse as an incubator host in order to compare the relative sensitivities of mammalian skin to hydrocarbon carcinogens. This would provide direct information concerning whether major species differences exist as well as provide a measure of the magnitude of these differences under identical environmental and experimental conditions.

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HEALTH CONSEQUENCES OF NITROGEN DIOXIDE EXPOSURE

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Biological effect of oxides of nitrogen have been evaluated in animals and man. Of the oxides of nitrogen which have been studied and which occur in the atmosphere through combustion of fossil fuels and subsequent conversion processes, nitrogen dioxide (NO_2) is the most toxic. Our knowledge of the toxicity of NO_2 is still incomplete. Yet, significant knowledge has been gained about its overall toxicity from the study of (1) exposed animals, (2) individuals, and (3) communities.

RESTRICTED EVALUATION

Evaluation of the health effects of NO_2 , demonstrated in all three of the above major experimental approaches, permits improved understanding when taken as a whole. In clinical human studies, safety of the volunteer is of paramount importance. Therefore, chronic exposures cannot be performed and only limited endpoints such as pulmonary function, clinical chemistry, and the like which are relatively benign can be used. This leads to a restricted evaluation of NO_2 effects. However, the research is highly controlled and the concentration and time of exposure to NO_2 can be directly related to the observed effects in man.

BIOLOGICAL PARAMETERS LIMITED

Information from population exposure studies is of value since humans are investigated under natural conditions. However, this natural condition is so complex, particularly with respect to individual exposure differences within the population, that it is extremely difficult to relate a particular pattern of NO_2 exposure to health effects. Again, for ethical reasons, biological parameters are limited.

The strength of animal toxicological studies lies in the unlimited exposure conditions and biological endpoints that can be used. Since animals and man have

extensive physiological similarities, if a particular effect occurs in a number of animal species, it is likely that this same effect occurs in humans. However, at this time, it is not possible to extrapolate directly from animal studies to those concentrations of NO_2 which will cause toxicity in man. With this as background, the review of the health effects of NO_2 can be placed into better perspective. Several other excellent reviews are available (1-3) and an Ambient Air Quality Criteria Document for Nitrogen Oxides is presently being prepared by the Environmental Protection Agency.

ANIMAL TOXICOLOGICAL STUDIES

Superficially, there appears to be a great similarity between the toxicity of NO_2 and ozone. A detailed analysis of the toxicity of NO_2 , however, reveals that there are as many dissimilarities as similarities. A summary of the research findings is in Table 1. An unusual aspect of the toxicity of NO_2 is a delay between exposure and effect. This temporal sequence is inherent in understanding the toxicity of NO_2 and has important implications for the effects of both short-term and long-term exposures to this air pollutant. Despite the differences in NO_2 sensitivity between animal species and the many different endpoints of toxicity, the sequence of events seems to be the same. The sequence of events is illustrated in Figure 1. A composite has been drawn from these different studies to illustrate the relationship with time following a single short-term exposure of 4 hours or less. These results are drawn primarily from a single species, the rat. A similar type of sequence could be drawn for other species. It is likely that this sequence is the same for all mammalian species exposed under similar conditions. These reactions will be obtained predominately with low concentrations of NO_2 . As the concentration of NO_2 is increased more than 100-fold over ambient concentrations, complications arise which tend to obscure the sequence of events. It is not clear, further, whether or not these higher concentrations are truly relevant to the toxicity of NO_2 to man as it occurs in the atmosphere of urban areas. In any event, the animal studies most important to determining the standards used in regulating emissions are those more closely aligned to ambient concentrations of NO_2 .

CELLULAR REACTION

Studies of the reaction of NO_2 with cellular constituents clearly illustrate that the chemical reactions are essentially instantaneous (4,5) when compared with the length of time required for demonstration of a biological effect. Most investigators believe that the chemical reactions of NO_2 are dominantly with lipid components of the cell (5). The reaction of NO_2 with the unsaturated lipids of cellular membranes

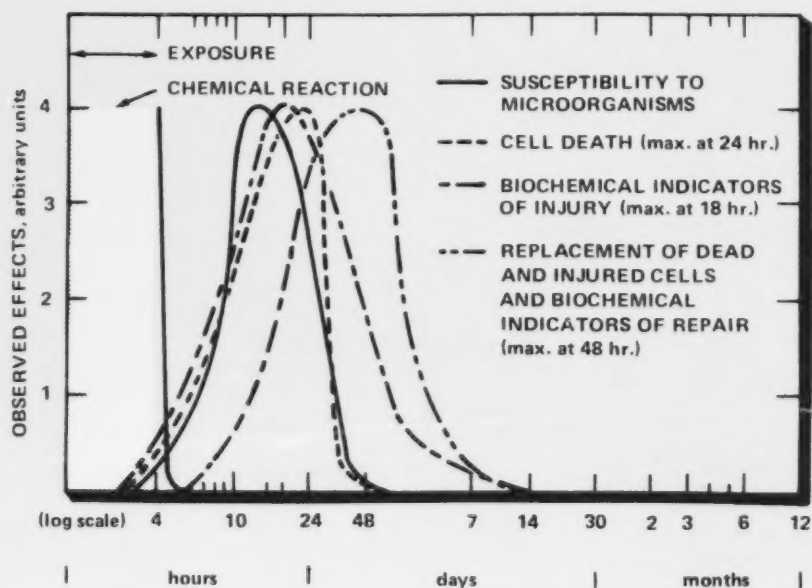


FIGURE 1—Temporal sequence of injury and repair hypothesized from short-term single exposures of less than 8 hours

TABLE 1
Effects of nitrogen dioxide in animals

Concentration of NO ₂		Time of Exposure	Species	Summary of Effects	References
ppm	μg/m ³				
0.1 + 2 hr daily spike of 1	188 + 2 hr daily spike of 1,880	Continuous 6 mo	Mice	Emphysematous alterations	82
0.25	470	4 hr/day 5 days/wk 24 or 36 days	Rabbits	Swollen collagen fibers in lung	32
0.3 - 0.5	560 - 940	Continuous 3 mo	Mice	NO ₂ + influenza virus caused a high incidence of adenomatous proliferation of peripheral and bronchial epithelial cells	29
0.32	600	3 mo	Rats	Decreased conditioned reflexes	83
0.36	680	7 days	Guinea Pigs	Increased erythrocyte D-2, 3-diphosphoglycerate	84
0.4	740	4 hr/day 7 days	Guinea Pigs	Increase in lung acid phosphatase	85
0.4	740	Continuous 1 wk	Guinea Pigs	Increase in protein of lung lavage	12
0.5	940	6,18, or 24 hr/day 12 mo	Mice	Morphological effects in alveoli	86
0.5	940	8 hr/day 7 days	Guinea Pigs	Increase in serum LDH, CPK, SGOT, SGT and cholinesterase, and lung and plasma lysozyme. Decrease in erythrocyte GSH peroxidase. No change in lung GSH peroxidase.	17, 18
0.5	940	Continuous 14 days	Guinea Pigs	Albumin and globulins in urine	87
	1,000 NO _x (mostly NO ₂)	8 hr/day 180 days	Guinea Pigs	Nitrates and nitrites in urine; slight increase in serum cholesterol; decrease in total serum lipids, hepatic edema; increase in urinary Mg and decrease in liver and brain Mg	88
0.5	940	Continuous 30 - 45 days	Mice	Morphological alterations of tracheal mucosa and cilia	89,90

(continued)

TABLE 1 (continued)

Concentration of NO ₂		Time of Exposure	Species	Summary of Effects	References
ppm	µg/m ³				
0.5	940	5 days/wk 7 wk	Mice	Increase of injected horseradish peroxidase in lung	91
0.5	940	Continuous 8 hr/day 4 mo	Guinea Pigs	Decrease in plasma cholinesterase; erythrocyte or lung GSH peroxidase unchanged. Increase in lung acid phosphatase and plasma and lung lysozyme	17,18
0.5 or 2	940 or 3,760	Continuous with 1 hr peaks of 2 ppm 5 days/wk	Mice	Morphological alterations of alveolar macrophages; decreased serum neutralizing antibody to influenza virus immunization; changes in serum immunoglobulins	92,93
0.5	940	Continuous 12 mo	Mice	At 10 days — damage to clara cells and cilia and alveolar edema. At 35-40 days — bronchial hyperplasia. At 6 mo — fibrosis. At 12 mo — bronchial hyperplasia	94,95
0.5 or 1	940 or 1,880	Continuous 1 yr, 5 mo	Mice	No increase in lipofuscin or glutathione peroxidase	96
0.5 or 1	940 or 1,880	Continuous 1 yr, 6 mo	Mice	Growth reduced; vitamin E improved growth	97
0.5	940	Continuous or intermittent (7-8 hr/day)	Mice	Increased susceptibility to <i>K. pneumoniae</i> after 90 days continuous or 180 days intermittent exposure	25
0.53	1,000	180 days 8 hr/day	Guinea Pigs	Alterations in several serum enzymes	98
0.55-1.6	1,030-3,000	Continuous 5 wk	Mice	Cilia damaged; increased mucus secretion	99
0.8	1,500	Continuous 2.75 yr	Rats	Increase in respiratory rate	100,101
1	1,880	Continuous 2 wk	Rabbits	Decrease in lung lecithin synthesis after 1 wk; less marked depression after 2 wk	102
1-1.5	1,880-2,820	Continuous 1 mo	Mice	Hypertrophy of bronchiolar epithelium after 1-3 mo. After recovery from exposure, lymphocyte infiltration	103
1	1,880	Continuous 6 mo	Guinea Pigs	Inhibition of protein synthesis; decrease in body weight, total serum proteins, and immunoglobulins	105

(continued)

TABLE 1 (continued)

Concentration of NO ₂		Time of Exposure	Species	Summary of Effects	References
ppm	µg/m ³				
1	1,880	Continuous 493 days	Monkeys	Immunization with monkey-adapted influenza virus. Increased serum neutralizing antibody titers at 93 days of exposure. No change in hemagglutination inhibition titers; no effect on hematocrit or hemoglobin; increased leukocytes in blood. Slight emphysema and thickened bronchial and bronchiolar epithelium in virus-challenged monkeys	106
1.1	2,000	8 hr/day 180 days	Guinea Pigs	Plasma and liver changes decrease in albumin, serumucoid, cholinesterase, alanine and aspartate transaminases, increase in alpha and beta ₂ immunoglobulins	107
1.26	2,360	12 hr/day 3 mo.	Rats, before breeding	No effect on fertility, decrease in litter size and neonatal weight, no teratogenic effects	108
1.3-3	2,400- 5,200	2 hr/day 15 & 17 wk	Rabbits	Increased leukocytes in blood with decreased phagocytosis, decreased number of erythrocytes	109
1.5	2,800	Continuous or Intermittent (7 hr/day, 7 days/wk)	Mice	After 1 wk, increased susceptibility to <i>S. pyogenes</i> aerosol greater in continuous exposure group. After 2 wk, no significant difference between modes of exposure	24
2 or 3	3,760 5,600	3 hr	Mice	Increased susceptibility to <i>S. pyogenes</i> aerosol in mice exercising compared to those not exercising	21
2	3,760	3 hr	Mice	Increased susceptibility to <i>S. pyogenes</i> aerosol.	22
2	3,760	Continuous 1-3 wk	Guinea Pigs	Increased in number of lactic acid dehydrogenase positive lung cells (presumably Type II cells) with time of exposure	110
2	3,760	Continuous 3 wk	Guinea Pigs	Type II cell hypertrophy	111
2	3,760	Continuous 43 days	Rats	Between 72 hr - 7 days increasing loss of cilia and focal hyperplasia; by 14 days, cilia regenerated and recovery was evident at 21 days	26

(continued)

TABLE 1 (continued)

Concentration of NO ₂		Time of Exposure	Species	Summary of Effects	References
ppm	µg/m ³				
2	3,800	Continuous 14 mo	Rats and Monkeys	Polycythemia with or without NaCl. Hypertrophy of bronchiolar epithelium	112
2	3,800	Continuous 2 yr	Rats	Increase in respiratory rate; no change in resistance or dynamic compliance	9
2.3	4,280	17 hr	Mice	Decreased pulmonary bactericidal activity (no measurable effect at 1 ppm x 17 hr or 3.8 ppm x 4 hr)	113
2.7	5,000	8 wk	Rats	Decreased body weight	114
2.9	5,450	Continuous 20 days	Rats	Decrease in linoleic and linolenic acid of lung lavage fluid	23
2.9	5,450	24 hr/day 5 days/wk 9 mo	Rats	Decrease in lung compliance and volume; increased lung weight and decreased total lung lipid; decreased saturated fatty acid content of lung lavage fluid and tissue; increased surface tension of lung lavage fluid	115
3	5,640	4 hr/day 4 days	Monkeys	Thickening of basal laminar and alveolar walls; interstitial collagen	116
3.5	6,600	Continuous or intermittent (7 hr/day, 7 days/wk)	Mice	Increased susceptibility to <i>S. pyogenes</i> aerosol with increased duration of exposure. No significant difference between modes of exposure	24
4-7	7,500-13,000	Continuous 14 days	Mice	Increase of injected radio-labeled protein in lung	13
5-50	9,400-94,000	3 hr	Rabbits	No measurable effect on benzo (a)pyrene hydroxylase activity of tracheal mucosa	117
5	9,400	4 hr	Guinea Pigs	Increase in respiratory rate and decrease in tidal volume	118
5	9,400	4 hr/day 5 days/wk 2 mo	Guinea Pigs	Increased lung tissue serum antibodies	119
5	9,400	7.5 hr/day 5 days/wk 5.5 mo	Guinea Pigs	No increase in airflow resistance	118
5	9,400	14-72 hr	Mice	Increased lung protein by radio-label method	120

(continued)

TABLE 1 (continued)

Concentration of NO ₂		Time of Exposure	Species	Summary of Effects	References
ppm	µg/m ³				
5	9,400	Continuous 1 wk	Rats	Hyperplasia began by 3 wks	121
5	9,400	Continuous 2 mo	Monkeys	Increased susceptibility to <i>K. pneumoniae</i>	34
5-10	9,400-18,800	Continuous 90 days	Monkeys	Infiltration of macrophages, lymphocytes and some polymorphonuclear leukocytes; hyperplasia of bronchiolar epithelium and Type II cells	122
5-10	9,400-18,800	Continuous 90 days	Monkeys	No significant hematological effects	123
5	9,400	Continuous 133 days	Monkeys	Immunization with mouse-adapted influenza virus. Initial depression in serum neutralization titers with return to normal by 133 days. No change in hemagglutination inhibition titers or amnestic response	124
10-0.1	18,800 190	6 hr	Mice	No chromosomal alterations in leukocytes or primary spermatocytes	125
5	9,400	7.5 hr/day 5 days/wk 5.5 mo	Guinea Pigs	No increase in airflow resistance	118
5	9,400	14-72 hr	Mice	Increased lung protein by radio-label method	120
5	9,400	Continuous 1 wk	Rats	Hyperplasia began by 3 wks	121
5	9,400	Continuous 2 mo	Monkeys	Increased susceptibility to <i>K. pneumoniae</i>	34
5-10	9,400-18,800	Continuous 90 days	Monkeys	Infiltration of macrophages, lymphocytes and some polymorphonuclear leukocytes; hyperplasia of bronchiolar epithelium and Type II cells	122
5-10	9,400-18,800	Continuous 90 days	Monkeys	No significant hematological effects	123
5	9,400	Continuous 133 days	Monkeys	Immunization with mouse-adapted influenza virus. Initial depression in serum neutralization titers with return to normal by 133 days. No change in hemagglutination inhibition titers or amnestic response	124
10-0.1	18,800 190	6 hr	Mice	No chromosomal alterations in leukocytes or primary spermatocytes	125

results in a chemical reaction characterized by the formation of peroxidic products. This is a devastating event in terms of the organization and properties of the cellular membrane necessary to maintain the integrity of the cell. Many of the biological effects can be ascribed to the peroxidation of cellular membranes, the most obvious example of which is pulmonary edema, a commonly observed phenomenon on exposure to high concentrations of NO_2 . Inhaled NO_2 is rapidly taken up and distributed throughout the lung as has been determined using short lived radiotracer studies with $^{13}\text{NO}_2$ (6). A very significant fraction of NO_2 is retained in the lung. The fraction which has been retained probably represents that NO_2 which is chemically reactive with pulmonary tissue via peroxidation.

ACID ANHYDRIDE

NO_2 is an acid anhydride and reacts with water vapor at ambient concentrations in the air and more so at the increased temperature and humidity existing within the respiratory system. The exact chemical species which reaches the pulmonary surface to produce the observed lesions is most likely NO_2 , but HNO_2 and perhaps NO may be formed in the liquid lining the airways. HNO_2 and HNO_3 will be rapidly neutralized by the biological substances dissolved in the liquid layer lining the airways of the lung.

INJURY TO LUNG TISSUE

Despite the hydration of NO_2 by water vapor, a significant fraction of NO_2 is not removed in the upper airways and penetrates deep within the lung to produce its toxic effects. As a strong oxidant, NO_2 may also oxidize small molecular weight reducing substances and proteins within seconds to minutes. Reaction with unsaturated fatty acids to produce peroxidation is essentially instantaneous. It is not likely, so far as is known, that NO_2 reaching the respiratory portions of the lung would be able to penetrate the lung cells and attain a significant concentration within the blood. Nitrate is formed as a consequence of reactions with cellular constituents and has been detected in the blood and urine of animals exposed to NO_2 . Levels of nitrate attained during NO_2 exposure are unlikely to induce biological responses of the nature which have been observed. Because of the high reactivity of NO_2 , the predominant response observed on the inhalation of NO_2 is direct injury to the tissues of the lung. The effects on organs distal to the lung are likely to result from the production of secondary toxicants in the lung which are circulated to other parts of the body. A direct proof of this hypothesis of circulating toxins following inhalation of NO_2 has not been found, but effects on organs other than the lung have been found. The significance of these effects on other organs is not known as yet.

The major effect observed on NO_2 exposure is cellular injury and death which occurs among specific cell types within the lung during a period of less than 24 hours after inhalation (7). The magnitude and site of the injury resulting from NO_2 will depend upon the concentration of NO_2 which was inhaled; therefore, the absolute degree of response will depend upon both the rate and magnitude of respiration and the NO_2 concentration. The moderate solubility of NO_2 in water and the inability of the upper respiratory tract to remove all of the NO_2 which is inhaled results in injury to specific regions within the lung. At concentrations near those found in urban environments, the region of the lung bounded by the terminal and respiratory bronchioles and adjacent alveoli is that which is most affected (7,8,9,10). This region represents the terminal portion of the lung and is intimately involved in the exchange of oxygen and carbon dioxide. This is the region of the lung which is most essential for the maintenance of life. Some differences may exist between man and rodents because this region of the lung is proportionately much shorter in the rat than in man.

CELL TYPES AFFECTED

At high concentrations of NO_2 , that is above $9,400\mu\text{g}/\text{m}^3$ (5.5 ppm), segments of the upper airways may be affected as well as those around the alveoli. As cells are exposed to NO_2 and begin to die, protein and nucleic acid synthesis are stimulated in the surviving stem cells and a wave of mitosis occurs which reaches its maximum at about 48 hours during or after exposure. The type I cell of the lung (a thin, squamous cell across which gases are exchanged) appears to be the most sensitive and likely to be injured at lower concentrations than the type II cells (a cuboidal cell that produces surfactant) (11). The nature of this injury can be sufficiently severe that the cell dies, sloughs off, and leaves debris within the alveoli. Other cells in the upper airway, such as ciliated cells, are similarly sensitive and may be replaced by other stem cells known as Clara cells. These effects on the lung result in dramatic changes in its structure and cell composition.

BIOCHEMICAL INDICATORS

Biochemical indicators of this injury can be detected by a wide variety of means. One of the most sensitive biochemical indicators of injury to these cells is a change in cellular permeability which has been detected at concentrations as low as $752 \mu\text{g}/\text{m}^3$ (0.4 ppm) NO_2 (12,13). At this concentration, plasma proteins or radiolabeled albumin injected into the bloodstream of animals can be detected in the airways. Under normal circumstances, such exudates do not occur and represent a major change in the permeability of the cell to allow large protein molecules to escape into the airway. Cells which are resident within the airway, such as the pulmonary macrophage, are also damaged by inhaled NO_2 . NO_2 damage can be detected as major changes in the macrophage respiration (14,15). The death of macrophages may release proteolytic enzymes which can produce further alterations in the organization and morphology of the lung. Effects similar to those observed *in vivo* can be produced by exposing isolated pulmonary macrophages to NO_2 *in vitro*. The macrophage is particularly sensitive to NO_2 exposure. Paradoxically, biochemical parameters of injury often return to normal or near normal values within a week or two of cessation of exposure (16,17,18).

INFECTIVITY MODEL

Pulmonary defenses against infectious agents are affected by short-term exposures to NO_2 . The infectivity model in which pollutant-exposed animals receive an aerosol of live microbes has proven to be a particularly sensitive indicator of pulmonary injury and has been responsible for the development of most of the data indicating toxicity of NO_2 at low concentrations and short times of exposure (19,20,21). Mortality from exogenous infectious agents is influenced more in proportion to the concentration of NO_2 than the duration of exposure. This observation is consistent with the hypothetical temporal sequence of injury. Pulmonary damage occurs rapidly on exposure to NO_2 but its effects may be observed much later, depending upon the extent of damage and the system which has been used to measure the damage. The infectivity model tends to be an integral of many of the defensive mechanisms of the lung and, therefore, to reflect the overall damage which has occurred. Concentrations as low as $4,700 \mu\text{g}/\text{m}^3$ (2.5 ppm) may result in excess mortality from a single exposure of only 3 hours (22). The injury of a 3-hour exposure appears to be repaired within 24 to 36 hours after exposure.

In Figure 2, a short-term exposure of constant duration has been given to an animal and only one of the properties of intoxication is illustrated, the death of type I cells. Increasing concentrations of NO_2 are illustrated in this figure on the x axis. Thus, as the concentration of NO_2 is increased, the magnitude of cellular death increases while the time at which cell death occurs is constant. The magnitude of cell death is proportional to the logarithm of the concentration of NO_2 which has been inhaled. Increasing the total amount of NO_2 inhaled by manipulations in the respiratory pattern will likewise increase the magnitude of cell death, but not influence the time at which cellular death occurs. Eventually, sufficient cells will be injured to produce mortality during the peak wave of death of alveolar cells. Death through respiratory insufficiency and pulmonary edema, however, does not occur at concentrations achievable in the urban atmosphere. Concentrations greater than $47,000 \mu\text{g}/\text{m}^3$ or 25 ppm are necessary to achieve direct death. This is not to say, however, that severe pulmonary damage is not achieved at lower concentrations near those which occur regularly in urban areas.

LONG-TERM EXPOSURE

The delay between the end of exposure and observation of biological effect complicates the understanding of the effects of long-term exposure to NO_2 . This is especially so in cases resembling those that occur in the atmosphere where exposure to NO_2 may occur repeatedly over a short time period to relatively high concentrations. Figure 3 illustrates the sequence of events which is hypothesized to occur on continuous long-term exposure to NO_2 . The sequence of events is essentially similar to that in short-term exposure. The chemical reactions between the inhaled NO_2 and cellular constituents are instantaneous and achieve a constant level throughout the exposure. During the first 14 days of exposure, cell death and replacement of pulmonary cells are the dominant features. This is expressed as a wave of mitosis or cellular division which reaches its maximum about 48 hours after the onset of exposure. The extent of cell death is illustrated in Figure 2 and is proportional to the concentration of NO_2 . Likewise, all of the other indicators of NO_2 damage so far

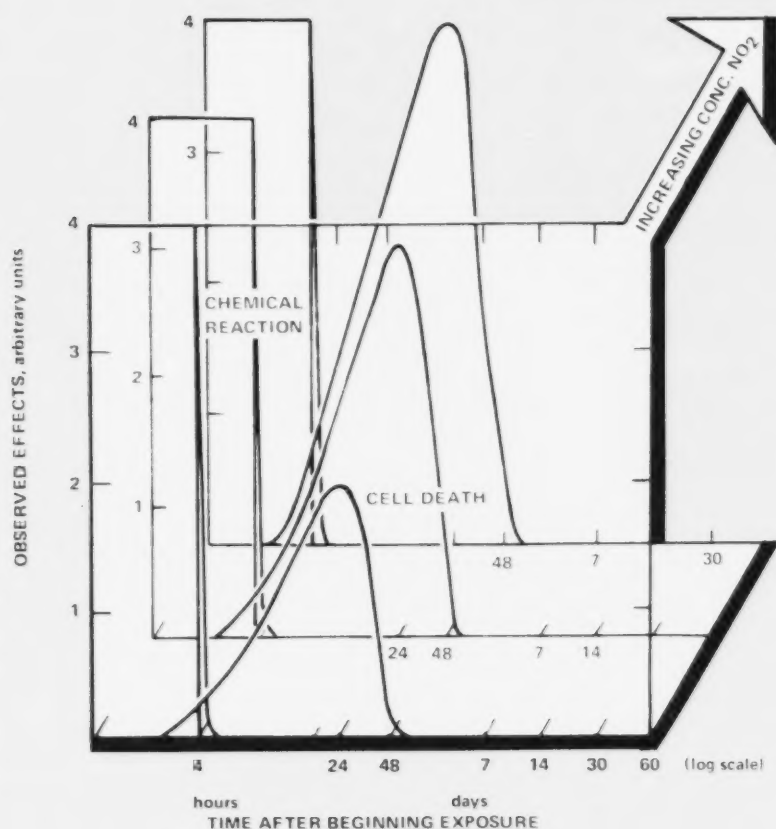


FIGURE 2—Proportionality between effect (cell death) and concentration of NO_2 during a constant exposure period. The maximum in cell death is reached ~ 18 hours after exposure and the extent is proportional to the dose (concentration $\times$ time)

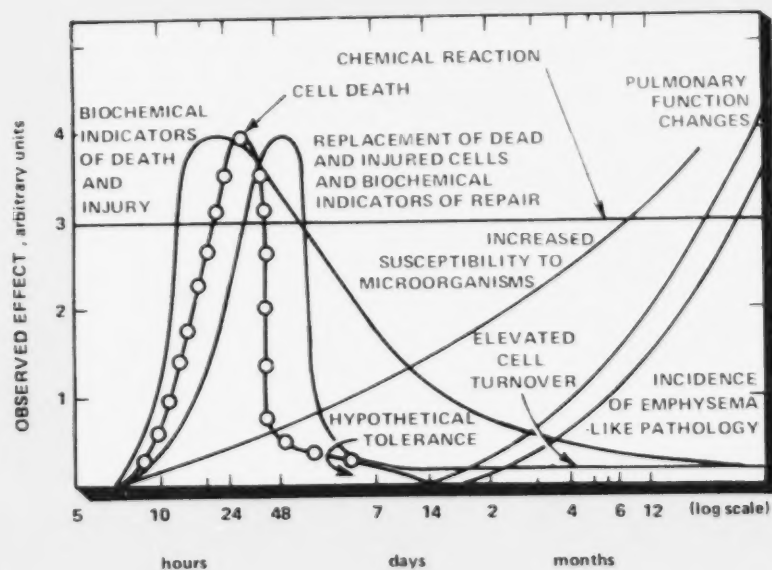


FIGURE 3—Temporal sequence of injury and repair hypothesized from continuous exposure to NO_2 as observed in experimental animals

examined are dose dependent. The biochemical and physiological functional indicators of damage change rapidly with injury and repair, reaching a relatively steady state after about a week or two (17,18,23). Several enzymes have been detected which are indicative of cellular injury at concentrations of NO_2 as low as $940 \mu\text{g}/\text{m}^3$ or 0.5 ppm during the injurious phase of continuous exposure, that is greater than 7 days. Pulmonary macrophages are aggregated within the lung and the degree of aggregation has been estimated by a number of biochemical techniques. Again, the infectivity model is highly sensitive to NO_2 exposure. The susceptibility to infection as measured by this technique rises almost linearly during this period. The infectivity model has been used to illustrate excess mortalities due to NO_2 exposure at concentrations within the range of $940\text{--}2,820 \mu\text{g}/\text{m}^3$ or 0.5–1.5 ppm NO_2 (24,25,27,28).

ALTERATIONS OF LUNG MORPHOLOGY

Long-term exposures to NO_2 also result in major alterations of lung morphology. These are very difficult to interpret because of the slow gradation of response once the initial phase of replacement of cells susceptible to NO_2 has passed (9,26,27,28). The development of an emphysema-like disease in experimental animals requires considerable time as has been demonstrated in studies of rats. The development of obstruction to airflow and distension and destruction of the alveolar tissue in experimental animals requires considerable time. When compared to the life span, the time required for damage in experimental animals is equivalent to that required for the development of emphysema in man. The process of emphysema development on NO_2 exposure is indeed complex, but it is clear that the effects are interpretable in terms of the changes in the cell populations and structural alterations concomitant to that. A major pathologic change is an increase in the distance between the air space and the capillary in the respirable or alveolar region of the lung (31–34). Other effects include the loss of ciliated cells which are responsible for removing particles from the lung and narrowing of the airways and alteration in the morphology of the cells lining the junction between the respiratory segment and the mucous containing segment (26,28). The cell type in the alveoli most sensitive to NO_2 , the type I cells, are replaced by type II cells, their progenitors, but the appearance of the type I cells maturing in the presence of NO_2 is significantly different from those in the absence of NO_2 (31). Other alterations in the lung include the appearance of collagen in areas which are normally devoid of this fibrous protein and the aggregation of macrophages (28,32). These effects have been observed in rats that have been exposed continuously to $3,760 \mu\text{g}/\text{m}^3$ (2 ppm) NO_2 or greater.

VITAMIN E AND NO_2

The fatty acid composition of the lung membranes has also been noted to change during the exposure to NO_2 (23). The mortality from continuous exposure to high concentrations of NO_2 is influenced by the level of vitamin E and other free radical scavengers which are included in the diet (23). These observations support the hypothesis that membrane damage by chemical oxidation of unsaturated fatty acids is a major mechanism of toxicity of NO_2 . These changes in fatty acid composition of the lung are accompanied by enzyme changes which in part may be protective and aid in the destruction of the peroxidic products formed in the lung on NO_2 inhalation (29). It should be emphasized that at no point is it possible to provide adequate levels of vitamin E or other dietary factors that provide complete protection against NO_2 . It should be noted, however, that certain segments of the population may be unusually sensitive to NO_2 should their intake of vitamin E and other antioxidants be marginal.

RESISTANCE AND RECOVERY

The temporal sequence of events suggests that the response of the animal to inhalation of NO_2 returns to near normal levels during continuous exposure. These results are misleading since it has clearly been observed in long-term studies of rats that the morphology of the lung has changed from its normal structure to that resembling emphysema (9,26,27). This raises the question of tolerance to resistance and recovery during continuous exposure. It is possible that, at some point, replacement of dead and injured cells resulting from the continuous inhalation of NO_2 may return to levels equivalent to that found in clean air (26). Tolerant cells, as compared with naive cells, may be more resistant to NO_2 because they are younger or because they may have

produced a protective mechanism such as specific increases in enzymes capable of degrading the secondary products formed on NO_2 inhalation. Some enzymes such as glutathione peroxidase, glutathione reductase, and glucose-6-phosphate dehydrogenase in the rat may be increased as a protective mechanism (16), or they more likely may reflect a proliferation of specific cells within the organ which contains higher concentrations. These cells are younger because they are dying and being replaced at a more rapid rate, at levels in excess of those which occur normally in the lung in pollutant free air. Not all species exhibit this protective induction of enzymes. For example, the guinea pig, when exposed to $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) NO_2 for 4 months failed to develop higher levels of these potentially protective enzymes (17,18). Importantly, when cultured lung cells are coated with a very thin layer of nutrients to resemble the condition within the lung, direct exposure to NO_2 is highly toxic.

APPARENT ADAPTATION

It is most likely that all cells are sensitive to relatively low concentrations of NO_2 and that no adaptation in the true sense ever occurs. The apparent adaptation that may be seen in pulmonary function measurements of people living in polluted areas vs. those that live in nonpolluted areas may be artifactual in the sense that large changes in pulmonary tissue may be necessary before permanent alterations may be detected in pulmonary function. In other words, a major patho-physiological change must occur before it is detected by these relatively insensitive pulmonary physiology methods. Biochemical and morphological techniques are more sensitive, but so invasive that they can only be used on experimental animals. In further support of the idea that all cells are sensitive to concentrations of NO_2 which are easily attainable in inhaled air, when rats have been exposed to $3,760 \mu\text{g}/\text{m}^3$ or 2 ppm NO_2 for long periods of time and then exposed to an abrupt increase in concentration of NO_2 , a second wave of mitosis and subsequent alterations in biochemical, physiologic, and morphologic indicators of cell damage occur in exactly the same temporal sequence (33). Thus, although adaptation may appear to occur, the ultimate development of an emphysema-like condition occurs in the rats on long-term exposure and they remain sensitive to alterations to higher concentrations of NO_2 .

TUMOR FORMATION

An important consideration has been the question of tumor formation of malignant metaplasia due to NO_2 exposure. This concern comes about due to the morphology of the lungs of animals which have been exposed to NO_2 . Because NO_2 produces a stimulation or rapid turnover of cells, a transient hyperplasia of the specific type II lung cell and nonciliated bronchiolar cell is observed. Such a hyperplasia represents a part of the natural repair mechanism. There is, however, no evidence to indicate that such changes represent tumor formation or malignant metaplasia. Thus, there is no data to connect the inhalation of NO_2 with an increased incidence of cancer at the present time.

CUMULATIVE EFFECT

We have come now to what is an important consideration of the effect of NO_2 on man. As was noted in the discussion of the effects of short-term exposure to NO_2 , the lag between exposure and biological effects. Such a cumulative effect has been demonstrated using the infectivity model in mice which were exposed continuously or intermittently (7 hr/day) to $2,820 \mu\text{g}/\text{m}^3$ (1.5 ppm) NO_2 (24). After 2 weeks of exposure, there was no difference in the pneumonia-related mortality between the intermittent and continuous exposure groups. Therefore, for the intermittent NO_2 treatment, the intervening 17 hours between exposures apparently were inadequate for complete recovery. Excess mortality could be shown at much lower concentrations on continuous exposure. Ninety days of exposure to concentrations as low as $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) resulted in significant mortalities (25).

The effects of NO_2 inhalation on the susceptibility to bacterial infections is not unique to the mouse. Other species of animals have been used including squirrel monkeys (39). The common thread of these experiments has been that the infectivity model is a good general indicator of damage by NO_2 . The direct extension of these data to man is difficult, in part because of differences in anatomical structure of the lung and in part because of differences in native and acquired immunity on the part of man. These data then should be viewed in terms of their indication of toxicity rather than in terms of their direct modeling of pulmonary infections in man.

In terms of the probable temporal sequence of events, NO_2 inhalation affects almost all of the cell types within the lung. Depending, then, upon the concentration of NO_2 , different cells will be affected in addition to those which are most susceptible at lower concentrations. The mode of exposure, that is the rate and depth of respiration, will also influence the specific cell types which are damaged. Because the rate of chemical reaction of NO_2 with cell constituents is almost instantaneous when compared to the time required for biological expression of injury, it may be expected that the concentration of NO_2 during a given exposure will have a greater effect on determining the end point used to measure toxicity than would the duration of exposure. Sensitive biochemical parameters are difficult to interpret because of the need to correlate biochemical changes with pathological processes. They are viewed, then, as indicators of death of specific cells or injury during the inhalation at the given concentration and extent and duration of exposure.

OTHER AIR POLLUTANTS

Because of the universal toxicity of NO_2 to pulmonary cells, it is likely that other air pollutants such as ozone, sulfuric acid, sulfur dioxide, and particulate matter may injure the same cells within the lung as are injured by NO_2 . In most cases, following the simultaneous inhalation of NO_2 and other air pollutants, additive, rather than synergistic effects, have been found. Tobacco smoking and occupational exposure add very significantly to the toxicity of NO_2 . At present, the data are not sufficient to provide a detailed evaluation of this important variable in the response of the population. Because of the delay between the exposure to NO_2 and effect, the sequence of exposures to air pollutants may be particularly important. Similar responses have been observed with ozone and sulfuric acid.

Another area of possible toxicity may be the formation of nitroso compounds, because nitrosamides and nitrosamines are known carcinogens. Nitrosamines and nitrosamides have recently come into the public view through their formation in foodstuffs containing nitrites. In this case, nitrite has been added to the foodstuffs to prevent bacterial contamination and spoilage. Gas phase reactions between NO_2 and amines to form nitrosamines have been reported, and inhaled, injected or ingested nitrosamines produce lung tumors in exposed animals. No evidence exists at the moment that nitrosamines or nitrosamides are formed in ambient air from nitrogen oxides, nor has it been demonstrated that they are formed *in vivo* in the lungs from the inhalation of NO_2 . Similarly, the role of inhaled nitrites and nitrates found in atmospheric particles is unknown and should be studied further. A few experiments indicate that inhaled nitrate produces biological effects through the release of histamine and other intracellular hormones. Whether such effects occur in man is not known. Continued surveillance of these important areas is needed.

CUMULATIVE EFFECTS

While much remains to be learned about the toxicity of NO_2 , studies so far conducted in animals indicate that the biological effects of NO_2 are likely to be displaced from the time of exposure. As shown in Figures 1 through 3, this delay between onset of symptoms and exposure to NO_2 may explain many of the confounding factors observed in epidemiologic data, but complicates further the question of effects of transient episodes of high NO_2 concentrations in the atmosphere. It is clear that the lowest concentration at which NO_2 , in particular, produces biological effects of a reproducible magnitude so far detected in animals is $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) after repeated exposure. The observation of cumulative effects is especially important, suggesting that under appropriate circumstances intermittent short-term exposure to NO_2 may eventually become equivalent to continuous long-term exposure. These observations, when compared with the data which have been accumulated on the long-term effects of NO_2 , may be particularly pertinent to the potential toxicity of this air pollutant to man. There is little doubt that the inhalation of NO_2 results in toxicity, regardless of the species which has been exposed. Thus, animal experiments are truly indicative of the hazard of this air pollutant to man.

HUMAN CLINICAL STUDIES

A number of investigators have examined the effects of NO_2 in human volunteers exposed for short periods of time under carefully controlled conditions. Although sensory effects have been found by several researchers (35-39) these effects are of uncertain significance. Therefore, the emphasis of this review will be on the NO_2 induced alterations of pulmonary functions. The summaries of the research findings are on Table 2.

TABLE 2
Effects of nitrogen dioxide in humans (clinical studies)

Concentration of NO ₂		Time of Exposure	Subject	Summary of Effects	References
ppm	μg/m ³				
0.05 NO ₂ 0.025 O ₃	94 50	120 min	Healthy	No effects on airway resistance; increased sensitivity to a bronchoconstrictor (acetylcholine)	41
0.1	188	60 min	Asthmatics	In 3 of 20 subjects — increased specific airway resistance; in 13 of 20 subjects — increased sensitivity to a broncho-constrictor (carbachol)	51
0.3 NO ₂ 0.5 O ₃ 30 CO	564 NO ₂ 980 O ₃ 45,900 CO	4 hr	Healthy	NO ₂ and CO did not alter the effect of O ₃ exposure on pulmonary function	54-56
0.5-5.0	940-9,400	15 min	Healthy	Only highest conc. caused effects: decreased arterial partial pressure of O ₂ ; no change alveolar partial pressure O ₂ ; decreased pulmonary diffusion capacity for CO; with exercise, increased airway resistance	40, 41, 42
0.5-5	940-9,400	15 min	Bronchitics	Effects only at 1.6 ppm and above — increased airway resistance. At 4-5 ppm, there was a decreased in arterial partial pressure of O ₂ and no change in alveolar partial pressure of O ₂	40, 42, 43
0.5	940	120 min	Healthy, brochitic, and asthmatics	No change in pulmonary function	50
0.61-1	1,147-1,880	120 min	Healthy	No observed effects on pulmonary function	44, 45, 46
0.7-2	1,317-3,766	10 min	Healthy	Increased inspiratory and expiratory flow resistance	48
2.25-7.5	4,230-14,000	120 min	Healthy	Increased airway resistance which did not increase as concentration was increased. No change in arterial or alveolar partial pressure of O ₂	46

(continued)

TABLE 2 (continued)

Concentration of NO ₂		Time of Exposure	Subject	Summary of Effects	References
ppm	μg/m ³				
2.5, 5, or 7.5	4,700, 9,400 or 14,100	120 min	Healthy	At higher concentration only, increased sensitivity to a bronchoconstrictor (acetylcholine)	46
3.6 NO ₂ + NaCl	5,640, 11,230 NO ₂ + 1,400 NaCl	Variable Sequence	Healthy	No effect from NaCl alone; increased airway resistance caused by NO ₂ even greater when NaCl included in exposure	52
4-5	7,520-9,400	10 min	Healthy	Increased expiratory and inspiratory flow resistance greatest 30 min. after exposure ended	47
5.0	9,400	14 hr	Healthy	Initial increase in airway resistance, followed by partial recovery, followed by even larger increase in airways resistance during exposure	46
5 NO ₂ 0.1 O ₃ 5 SO ₂	9,400 NO ₂ 196 O ₃ 13,000 SO ₂	120 min	Healthy	SO ₂ and O ₃ lengthened time of recovery from increased airway resistance	41
7	13,160	10-12 min	Healthy	Only some subjects showed increased airway resistance	43

EFFECTS FROM NO₂ ALONE

Much of this research has been conducted in the laboratory of von Nieding and his colleagues (40,41) who have studied both healthy and bronchitic subjects. Unfortunately, some of the techniques used for measurement of arterial partial oxygen pressure, airway resistance, and plethysmography are different from the typical systems used in this country. Because of this, it may not be possible to compare the data of von Nieding et al. with those of American investigators. Nonetheless, the same technique was used for a given study, and differences between functional measurements before and after exposure were found by von Nieding. So even though the absolute values of these changes may be subject to argument, the direction of the effects holds.

HEALTHY INDIVIDUALS EXPOSED TO NO₂

When von Nieding et al. studied 13 healthy individuals exposed for 15 minutes to 940-9,400 μg/m³ (0.5-5 ppm) NO₂, only the highest concentration was found to cause alterations in pulmonary function. There was a decrease in the arterial partial pressure of oxygen, but no change in the end-expiratory partial pressure of oxygen. The net effect was an increase in the alveolar-arterial difference in partial pressure of oxygen (AaDO₂). Such a change implies a decrease in the transfer of oxygen across the alveolar-capillary membrane. A similar effect was also found by von Nieding et al. (41) when 11 healthy subjects were exposed for 2 hours to 9,400 μg/m³ (5 ppm) NO₂. The subjects who had intermittent light exercise during exposure also exhibited increased airway resistance, a finding that suggests a narrowing of airway diameter. In an additional study by von Nieding (42), the pulmonary diffusion capacity for CO, which

reflects transfer of gas between the airspaces and the blood, was significantly decreased after a 15-minute exposure to $9,400 \mu\text{g}/\text{m}^3$ (5 ppm).

That individuals can differ in their sensitivity to NO_2 was demonstrated by Yokoyama (43) who exposed humans to concentrations of $13,161 \mu\text{g}/\text{m}^3$ (7 ppm) and higher for 10-12 minutes while some subjects experienced increases in airway resistance at $13,160 \mu\text{g}/\text{m}^3$ (7 ppm), others were not affected by $30,080 \mu\text{g}/\text{m}^3$ (16 ppm).

AIRWAY RESISTANCE

Investigations by Hackney (44) and Folinsbee et al. (45) employed measures of airway resistance and several additional functional endpoints. In these studies, exposure to $1,880 \mu\text{g}/\text{m}^3$ (1 ppm) or $1,146.8 \mu\text{g}/\text{m}^3$ (0.61 ppm) for 2 hours caused no significant effects on healthy individuals. A concentration of $1,880 \mu\text{g}/\text{m}^3$ (1 ppm) was also found to have no effect after 2 hours of exposure in a study performed by Beol and Ulmer (46). However, at $4,230 \mu\text{g}/\text{m}^3$ (2.25 ppm) and above, significant increases in airway resistance were observed which did not increase as concentration was increased up to $14,000 \mu\text{g}/\text{m}^3$ (7.5 ppm). There were no changes in the alveolar or arterial partial pressure of oxygen. When exposure to $9,400 \mu\text{g}/\text{m}^3$ (5 ppm) was lengthened from 2 hours to 14 hours, there was an initial increase in airway resistance during the first 30 minutes which returned towards normal during the second hour. However, during the continued exposure, even larger increases in airway resistance occurred between 6 and 14 hours of exposure. When exposure was repeated on 2 consecutive days, the airway resistance of the subjects was within normal values 10 hours after cessation of exposure. In another phase of the experiment, the sensitivity of exposed healthy individuals to a bronchoconstrictor agent (acetylcholine) was studied. After 2 hours of exposure to $14,100 \mu\text{g}/\text{m}^3$ (7.5 ppm), but not $4,700$ or $9,400 \mu\text{g}/\text{m}^3$ (2.5 or 5 ppm) NO_2 , there was an increased sensitivity to the drug. However, when the duration of exposure was lengthened to 14 hours, $9,400 \mu\text{g}/\text{m}^3$ (5 ppm) NO_2 did cause increased sensitivity to the bronchoconstrictor agent.

TIME COURSE OF NO_2 RESPONSE

In another study of the time course of the NO_2 response, Abe (47) showed that the increases in expiratory and inspiratory flow resistance from a 10-minute exposure to $7,520$ - $9,400 \mu\text{g}/\text{m}^3$ (4-5 ppm) were maximal 30 minutes after exposure terminated. At this time, compliance (a measure of lung distensibility) was also decreased.

Suzuki and Ishikawa (48) reported that healthy individuals exposed for 10 minutes to $1,316$ - $3,760 \mu\text{g}/\text{m}^3$ (0.7-2 ppm) had increased inspiratory and expiratory flow resistance. Unfortunately, some information on the variability of the data was not included in the report, and it was stated that NO_2 levels varied during exposure. These factors make an independent interpretation of the results difficult.

All the foregoing studies were made on healthy individuals. However, numerous disease states exist which could alter an individual's response to NO_2 . Studies delving into this complex problem of pollutant sensitivity have been performed by a few investigators.

EFFECTS ON CHRONIC BRONCHITIS

Von Nieding et al. (42) investigated the effects of a 15-minute exposure to $9,400 \mu\text{g}/\text{m}^3$ (5 ppm) NO_2 on chronic bronchitis. While there was no change in the alveolar partial pressure of oxygen, the arterial partial pressure of oxygen did decrease, resulting in an increased AaDO_2 , as found in healthy subjects. Even though exposure was continued for up to 60 minutes, further significant changes in these endpoints were not found.

In additional studies with up to 88 chronic bronchitics, von Nieding et al. (40,49) made observations on airway resistance as well as AaDO_2 . The patients were exposed for 15 minutes to between 940 and $9,400 \mu\text{g}/\text{m}^3$ (0.5-5 ppm). No significant alterations were found at $< 2,820 \mu\text{g}/\text{m}^3$ (1.5 ppm). However, at $> 3,008$ - $9,400 \mu\text{g}/\text{m}^3$ (1.6-5 ppm), a significant increase in airway resistance was observed and at $7,520$ - $9,400 \mu\text{g}/\text{m}^3$ (4-5 ppm) there was a significant decrease in the arterial partial pressure of oxygen and an increased AaDO_2 . On the other hand, after a 2-hour exposure to $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) with light to medium exercise of healthy, bronchitic and asthmatic subjects, Kerr et al. (50) found no significant changes in a number of pulmonary function parameters.

ASTHMATICS EXPOSED

Orehek et al. (51) exposed 20 asthmatics to $188 \mu\text{g}/\text{m}^3$ (0.1 ppm) NO_2 for 1 hour. In 3 of the 20 subjects, there were marked increases in specific airway resistance after NO_2 exposure. In another phase of the study, the sensitivity of the patients to a bronchoconstrictor agent (carbachol) was studied. In 13 of the 20 exposed subjects, there was an increased sensitivity to carbachol. This study is subject to controversy from a statistical viewpoint and because an extremely sensitive technique (i.e., sensitivity to a bronchoconstrictor agent) was employed. Although from this study it is not possible to conclude that short-term exposure to $188 \mu\text{g}/\text{m}^3$ (0.1 ppm) has an adverse effect, the findings have public health implications which must be defined further by replication of the study. In the Beil and Ulmer (46) von Nieding, et al. (41) and Orehek, et al. (51) studies, cholinergic stimulation of the upper airways demonstrated the greatest airway sensitivity to NO_2 inhalation. It could be argued that such stimulation is artifactual and nonphysiologic. On the other hand, the role of cholinergic innervation and cholinergic receptors in vasoactive hormone release and bronchial tone in man is well established. Cholinergic pathways may be highly stimulated in atopic individuals, especially asthmatic and bronchitic patients. Since atopy is a relatively common trait in man, these studies bear confirmation and further study. NO_2 may well cause the release of vasoactive hormones, alter bronchial tone or increase mucus secretion. Such effects would tend to exacerbate pre-existing disease and to accelerate the natural course of bronchitis and asthma in man.

EFFECTS FROM NO_2 WITH OTHER POLLUTANTS

In the natural environment, man is exposed to a complex mixture of pollutants. The variety of this mixture with respect to the type of pollutants, concentrations, and time patterns of occurrence make evaluation of the effects of pollutant combinations inherently difficult. Several interesting relationships have been elucidated in the work that has been done, but much remains to be understood.

Nakamura (52) investigated the effect of NO_2 in combination with an aerosol of NaCl (mean diameter $0.95 \mu\text{m}$) on airway resistance. The exposure regimen was varied and involved a 5 minute exposure to $1,400 \mu\text{g}/\text{m}^3$ NaCl alone, a rest period of 10 to 15 minutes a 5 minute exposure to $5,640$ or $11,280 \mu\text{g}/\text{m}^3$ (3 or 6 ppm) NO_2 , a rest period of 10 to 15 minutes and a final 5-minute exposure to a combination of the same concentrations of NaCl and NO_2 . The NO_2 exposure alone caused increased airway resistance (at each concentration), whereas NaCl alone produced no effect. In combination, the increase in airway resistance was about twice that produced by the gas alone. Schlipkoter and Brockhaus (53) showed that exposure to $9,024 \mu\text{g}/\text{m}^3$ (4.8 ppm) NO_2 increased retention of inhaled dust. In the natural setting, if the inhaled dust were toxic, it is likely that NO_2 would increase its toxicity.

INTERACTION OF GASES

In an investigation of the interaction of gases, von Nieding et al. (41) exposed healthy subjects for 2 hours to NO_2 ($9,400 \mu\text{g}/\text{m}^3$, 5 ppm) in combination with ozone ($196 \mu\text{g}/\text{m}^3$, 0.1 ppm) or the same concentration of ozone plus sulfur dioxide ($14,300 \mu\text{g}/\text{m}^3$, 5 ppm). The major effect of combining ozone or ozone plus sulfur dioxide with NO_2 was to lengthen the time required for recovery from the increased airway resistance. von Nieding et al. (41) also studied the effects of different concentrations of these gases in combination. The 2-hour exposure of healthy subjects was to $94 \mu\text{g}/\text{m}^3$ (0.05 ppm) NO_2 , $49 \mu\text{g}/\text{m}^3$ (0.025 ppm) O_3 and $314 \mu\text{g}/\text{m}^3$ (0.11 ppm) SO_2 . There was no effect on airway resistance or the AaDO₂. However, this exposure did increase the individual's sensitivity to a bronchoconstrictor.

Different mixtures of gases were investigated by Hackney et al. (54-56). For 4 to 5 hours, healthy humans were exposed to O_3 , O_3 plus NO_2 , or O_3 , NO_2 , and CO . The following concentrations were employed: $980 \mu\text{g}/\text{m}^3$ (0.5 ppm) O_3 , $564 \mu\text{g}/\text{m}^3$ (0.3 ppm) NO_2 , and $34,500 \mu\text{g}/\text{m}^3$ (30 ppm) CO . The minimal alterations in pulmonary function which occurred after O_3 exposure were not increased by the addition of NO_2 or NO_2 plus CO .

The epidemiological studies demonstrate increased risk of acute respiratory disease and diminished lung functions particularly among school children exposed to community air containing NO_2 , sulfur oxide, particulate matter, and in some cases photochemical oxidants. In many cases, it is difficult to determine whether a given level of NO_2 was

responsible for the observed health effects, or whether one of the other pollutants, alone or in combination with NO_2 , was the causative agent. However, it is significant that the reported studies directly support evidence from animal experiments and from controlled human studies of increased risk of acute respiratory infection and alteration in normal lung function. Interpretation of the data is complicated because of the complex variety of pollutants constantly present in the ambient atmosphere and the difficulty in defining actual exposure of the study population. Furthermore, those studies conducted before 1973 are of questionable validity due to a number of instrumental and analytical difficulties inherent in the techniques used for measuring atmospheric concentrations of NO_2 . Nevertheless, the existing data do not contradict the findings that pulmonary effects are related to NO_2 exposure. These studies are described on Table 3.

PULMONARY TESTS OF SCHOOL CHILDREN

The Chattanooga, Tennessee study conducted by Shy et al. (57-59), was designed to detect changes in pulmonary function in school children living in a high, intermediate, or low concentrations of NO_2 . The results of these studies were of borderline significance and consequently the association of impaired lung function with higher NO_2 concentration is not strongly supported. In these studies it is estimated that the annual means of daily NO_2 concentrations at the industrial area of high NO_2 was approximately $280 \mu\text{g}/\text{m}^3$ (0.15 ppm). The validity of results of this study has been questioned because direct measurement of NO_2 could not be used and because significant concentrations of sulfate and nitrate particulate seem likely to have been present. It is possible that the particulate matter may have been a contributing cause of any observed adverse effects measured. Several years later, Hasselblad, (60) performed an additional study in the same areas of Chattanooga to investigate whether the exposure to air pollutants during early life might have produced effects in children that persisted for a number of years. Analysis of these data showed that the population living in the intermediate and low pollution areas had no statistically significant impairment of pulmonary function, suggesting that the effects observed earlier were reversible and that recovery was essentially completed after 3 years.

PULMONARY TESTS OF POLICEMEN

Speizer and Ferris, (61) studied 268 policemen in urban Boston who were exposed to a spectrum of levels of automobile exhaust as traffic officers, patrol car officers, and indoor clerical officers. The mean 24 hour NO_2 concentrations (as determined from 1-hour sampling data using the Saltzman technique) were $100 \mu\text{g}/\text{m}^3$ (0.055 ppm) in the downtown urban area, and $75 \mu\text{g}/\text{m}^3$ (0.04 ppm) in the suburban area. The test results were standardized for age, height, and cigarette smoking habits. No differences in pulmonary function were observed in these studies.

Cohen et al. (62) compared a variety of pulmonary functional tests in nonsmoking Seventh Day Adventists living in Los Angeles with others of the same religious affiliation living in San Diego. The average NO_2 concentration in the Los Angeles Basin was $96 \mu\text{g}/\text{m}^3$ (0.05 ppm). In San Diego the levels were much lower. No group differences in lung functions were detected in these studies.

JAPANESE TEST RESULTS

Mogi et al. (63) and Yamazaki et al. (64) studied Japanese employees who worked in areas where the NO_2 concentration could be classified as medium, light, or no pollution. Mean NO_2 concentrations measured by the Saltzman method, ranged from $300\text{--}1,130 \mu\text{g}/\text{m}^3$ (0.16-0.60 ppm). Test results obtained showed a decrease in pulmonary function which did not correlate with the NO_2 concentration in the working area of the people. Kagawa et al. (65) and Kagawa and Toyama (66) studied the weekly variation in pulmonary function of normal school children in Tokyo in relation to variation in temperature and ambient concentrations of O_3 , NO , NO_2 , hydrocarbons, SO_2 , and particulate matter. In these studies, temperature was the factor most closely correlated with variation in specific airway conductance and maximum expiratory flow rate at 25 percent and 50 percent forced vital capacity. Negative correlations were observed in sensitive children between O_3 and specific airway conductance, and between NO_2 , NO , SO_2 , and particulate matter at V_{max} at 25 percent and 50 percent forced vital capacity. The range of hourly NO_2 concentrations at the time of the lung function tests, which was used for correlation during the period of study during the high temperature season, was approximately $40\text{--}360 \mu\text{g}/\text{m}^3$ (0.02-0.19 ppm).

EXPOSURE-HIGH AREAS

Using animal models there have been numerous reports that both continuous and intermittent exposure to low concentrations of nitrogen dioxide can alter the host respiratory defense mechanisms making the individual more susceptible to respiratory infections. Based on this information, epidemiological studies have examined the effects of NO₂ on acute respiratory illness. In a similar study, Poljak also reported that a population residing within 1 Km of the chemical works in the Soviet Union had more visits to the health clinic for respiratory, and other disorders than did a population living more than 3 Km away. In this study also, the NO₂ was combined with high concentrations of SO₂ and H₂SO₄ which may well have accounted for the observed respiratory effects. Shy et al. (58, 59, 67) as a part of the Chattanooga, Tennessee study, evaluated the frequency of acute respiratory disease in children and their parents living near a large point source of nitrogen dioxide. Three populations were studied—one close to the source with high NO₂ exposures and two with low NO₂ exposures. The total study

TABLE 3
Effects of nitrogen dioxide on humans (community studies)

A. Pulmonary function					
Concentration Measure	Concentration of NO ₂		Study Group	Summary of Effects	References
	ppm	µg/m ³			
$\bar{x}$ annual 24 hr high area	0.055 + 0.035 SO ₂	103 + 92 SO ₂	Policeman in urban Boston vs suburban areas	No difference in pulmonary function	61
low area	0.04 + 0.014 SO ₂	75 + 36 SO ₂			
1 hr $\bar{x}$ high area	0.14 to 0.3	260 to 560			
low area	0.06 to 0.09	110 to 170			
$\bar{x}$ annual 24 hr high area	0.05	96	Nonsmokers in Los Angeles vs San Diego	No difference in pulmonary function	62
low area	0.01	43			
Est. 1 hr max high area	0.26 to 0.51	480 to 960			
low area	0.12 to 0.23	205 to 430			
1 hr	0.02 to 0.19	40 to 360	11 yr olds	Temperature most correlated with pulmonary function changes in sensitive children. Specific airway conduction negatively correlated with NO ₂ , NO, SO ₂ and particulates. At high temperature, VMAX and specific airway conduction negatively correlated with NO ₂ , SO ₂ , and particulates	65, 66
Est. 1 hr max high area	0.75 to 1.5	1,400 to 2,800	children	Decreased forced expiratory volume in high concentration area. Differences are of borderline significance.	57-59
low area	0.4 to 0.8	750 to 1,500			

(continued)

TABLE 3 (continued)

B. Acute and chronic respiratory disease					
Concentration Measure	Concentration of NO ₂		Study Group	Summary of Effects	References
	ppm	µg/m ³			
NO ₂	0.31 to 0.64	580 to 1,200	Adults within 1 Km of chemical plant vs adults >3 KM away from plant	Subjects living close to plant had 44% more visits to health clinic	67
SO ₂	0.12	225			
H ₂ SO ₄		400			
High area	0.08–0.14	150 to 282	871 families	Respiratory illness rate:	58, 59, 67, 68
NO ₂	<0.01	<26	Families with children born 1966–68	Children 22.1%	
SO ₂		13–4		Siblings 18.8%	
suspended sulfates (SS)		7–4		Mothers 14.2%	
suspended nitrates (SN)				Fathers 12.1%	
total susp. particles (TSP)		96–93		School children born 1966–68	
Intermediate area					
NO ₂	0.06	113		Respiratory illness rate:	
SO ₂	<0.01	<26		Children 18%	
SS		10		Siblings 15.6%	
SN		3		Mothers 11.8%	
TSP		62		Fathers 8.8%	
				Bronchitis rate: 31.2% for children in area ≥3 yr	
Low area					
NO ₂	0.03	56		Respiratory illness rate:	
SO ₂	0.01	26		Children 20.1%	
SS		10		Siblings 17.0%	
SN		2		Mothers 12.3%	
TSP		62		Fathers 9.6%	
Annual $\bar{x}$					
NO ₂	0.05	96	Nonsmokers in Los Angeles	No difference in prevalence of chronic respiratory disease	76
O ₃	0.046	92			
NO ₂	0.023	42	Nonsmokers in San Diego		
O ₃	0.038	76			

(continued)

included 4,043 individuals. After adjusting for group differences in family size and composition, the incidence of acute respiratory disease in the high exposure population was found to be 19 percent higher than in the two comparison groups. In this study, NO₂ concentrations were determined by the Jacob-Hochheiser method. This method of analysis has been criticized for a variety of reasons, and thus the data were re-examined using analysis obtained by the more acceptable Saltzman method. The reevaluation indicated that the largest group differences in pollutant exposures were in the NO₂ and suspended nitrate. However, it is known that H₂SO₄ and nitric acid aerosols were also present in the atmosphere during this epidemiological study. As in all complex low-level exposures, it is extremely difficult to identify which particular individual pollutant at any concentration of exposure is the sole cause of the effect.

TABLE 3 (continued)

Concentration Measure	Concentration of NO ₂		Study Group	Summary of Effects	References	
	ppm	µg/m ³				
Median hr						
high						
NO ₂	0.07	130	Office workers in Los Angeles vs San Francisco	No difference in prevalence of chronic respiratory disease	77	
O ₃	0.07	137				
low						
NO ₂	0.035	65				
O ₃	0.02	39				
Annual $\bar{x}$ NO ₂	0.042	79	Women	Bronchitis rate <5% in areas having <0.042 ppm NO ₂ . High conc. of TSP present	69	
1/2 to 1 hr	0.5 to 1.0	940 to 1,880	Women cooking with gas stoves vs electric stoves	No increased respiratory illness	70	
					71	
NO ₂	0.25 to 0.5	470 to 940	Children from homes using gas stoves vs electric stoves	Homes with gas stoves: increased bronchitis, coughing, and wheezing	72	
Annual $\bar{x}$ NO ₂ SO ₂	0.04-0.055	75-103	Policeman in urban Boston vs suburban	Small (not statistically significant) increase in chronic respiratory disease of some subgroups in urban Boston	74	
Annual $\bar{x}$ 6-70 to 12-70						
high	0.05	92	Adults	Prior exposure to higher concentrations had no influence on effects observed	75	
intermediate	0.04	71				
low	0.03	58				
12-67 to 11-68						
high	0.08-	15-282				disease
intermediate	0.15	117				early advanced
	0.06			% prevalence of chronic bronchitis	30 11	
low	0.06	117			33 20	
					25 13	

STUDY OF SCHOOL CHILDREN

In a retrospective study in the same area, Pearlman et al. (68) determined the frequency of lower respiratory disease among school children born between 1966 and 1969 in an area of high NO₂ exposure. The responses were validated by physicians and hospital records. Bronchitis rates per hundred children were highest in the areas of maximum NO₂ concentration. For children who had lived in the same neighborhood for 3 or more years, the bronchitis rate in the areas of high NO₂ concentration were greater than those for children living for comparable periods in low concentration areas. Bronchitis rates for children in the intermediate area were nearly as high as those determined from the children in the area of high NO₂ exposure. However, the bronchitis rate in children who had lived in the area for less than 2 years did not follow the exposure gradient.

CHRONIC BRONCHITIS STUDY

A study (69) of chronic bronchitis among Japanese housewives living in six localities throughout Japan was conducted during the winter of 1970 and 1971. The prevalence rate of chronic bronchitis was found to exceed 5 percent only in those areas where the annual NO_2 concentration was $79 \mu\text{g}/\text{m}^3$ (0.042 ppm) or above. This Japanese study was confounded by high total suspended particulates ranging from 2-6 times the United States primary standard, which could not be appropriately disentangled from the effects of NO_2 alone.

Investigators from the Environmental Protection Agency (70) compared the incidence of acute respiratory disease among housewives cooking with either gas or electric stoves. Because of the high flame temperatures, the gas stove produced peak concentrations of NO_2 as high as $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) for durations of 1/2 to 1 hour each time the gas stove was used in preparing meals. Electric stoves which operate at lower temperatures do not form NO_2 . In this comparative study, no difference in incidence of respiratory disease was evident. A similar study by Mitchell et al. (71) determined the incidence of respiratory disease in Ohio middleclass families with gas stoves and electric stoves. Health data were obtained through biweekly telephone calls for one year. No difference in respiratory disease was detected. In these studies, the reported peak NO_2 concentration in homes with gas stoves was as much as eight times higher than the 24 hours means, and sometimes exceeded $1,900 \mu\text{g}/\text{m}^3$ (1 ppm).

INCREASED ILLNESS RATES

A study of children in England and Scotland showed increased illness rates in those living in homes with gas stoves compared with children from homes with electric stoves (72). In this study, the analysis of data collected took account of the individual's social class, age, population density, family size, crowding in the homes, outdoor level of smoke and sulfur dioxide, and type of fuel used for heating in the home. However, the smoking habits of the parents were not determined. The prevalence of bronchitis in the homes using gas stoves was 5.7 percent and 4.7 percent for boys and girls, respectively. In the homes with the electric stoves, the prevalence was 3.1 percent and 2 percent. It was also noted that girls in the homes of gas stoves had a significantly higher prevalence rate for morning cough and for wheeze. The investigators concluded that the elevated levels of NO_x might have caused the increased respiratory illness.

These studies provide evidence of increased occurrence of acute illness in areas in which ambient concentrations of NO_2 are high. The data suggest that peak hourly concentrations in the range of 470 - $1,880 \mu\text{g}/\text{m}^3$ (0.25-1.0 ppm) may be associated with the occurrence of a greater number of respiratory illnesses. However, it should be noted that the epidemiological studies on acute respiratory disease and populations exposed for long periods to elevated NO_2 concentrations, provide evidence to support the animal data on NO_2 , which indicates that NO_2 can impair resistance to respiratory infections. However, in many of these studies, it is difficult to determine whether a given concentration of NO_2 was responsible for the observed health effects or whether one of the other pollutants, alone or in combination was the causative agent. In many instances, the concentration of materials such as suspended sulfates or nitrates were not monitored, and the concentration of potentially toxic acids (such as nitrous and nitric, sulfurous and sulfuric) that represent the intermediate products of the transformation also were not determined. These other pollutants also could have attributed to the adverse health effects observed.

RESPIRATORY DISEASE AND POPULATION EXPOSURE

A few epidemiological studies concerned with the relationship between chronic respiratory disease prevalence and population exposures to NO_2 have also been conducted. One such study (69) conducted in 1970 and 1971 examined young Japanese housewives and these investigators found that the prevalence of chronic bronchitis exceeded 5 percent in those areas where the overall NO_2 concentration was $70 \mu\text{g}/\text{m}^3$ (0.042 ppm). However, at the time of this study, there were also extremely high levels of total suspended particulate which may have contributed to the observed effect. Fujita et al. (73) compared the prevalence rate of chronic bronchitis among postal workers in 1962 vs. 1967 and reported that there was an overall increase rate of chronic bronchitis in 1967 vs. 1962. These researchers believed that the concentration of NO_2 was higher in the later years, however there were no data to substantiate this claim. The aerometric data available for this study was insufficient to show any meaningful association between the prevalence of chronic bronchitis and any single pollutant such as NO_2 .

FOOT PATROL/ PATROL CAR STUDY

In Boston, Speizer and Ferris (74) compared the prevalence of chronic respiratory disease among policemen who patrolled on foot in congested business areas of Boston with that of suburban patrol car officers. The exposure of each group to NO_2 was determined at several work locations for the central city officers as well as the officers in the patrol cars. The annual mean pollution levels, based on hourly samples, were $103 \mu\text{g}/\text{m}^3$ (0.055 ppm) NO_2 and $90 \mu\text{g}/\text{m}^3$ (0.05 ppm) SO_2 for the urban area. The suburban area averaged $75 \mu\text{g}/\text{m}^3$ (0.04 ppm) NO_2 and $26 \mu\text{g}/\text{m}^3$ (0.01 ppm) SO_2 . The urban policemen who had spent more time in heavy traffic exhibited a small, but not significant, increase in chronic respiratory disease in nonsmokers and current smokers. No effect was seen in exsmokers.

A number of other studies also failed to establish an association between prevalence of chronic bronchitis and exposure to concentration of NO_2 in the ambient environment. Chapman et al. (75) studied the prevalence of chronic bronchitis in 3,500 parents of high school children living in three different areas of Chattanooga. In this test area, higher NO_2 concentrations had been present during the years of 1966 to 1969 than were present at the time of this study (1970). These authors failed to find any correlation between the concentration data for either period and the prevalence of chronic respiratory illness in the studied populations. Similarly, Cohen et al. (76) also found no difference in the prevalence of chronic respiratory disease between the non-smoking population in San Diego as compared with a similar population in Los Angeles. The Los Angeles group was exposed to levels of NO_2 between 90 and $100 \mu\text{g}/\text{m}^3$ (0.05 ppm) plus an oxidant level of about $90 \mu\text{g}/\text{m}^3$ (0.045 ppm); the San Diego group was exposed to lower levels of NO_2 of approximately $40 \mu\text{g}/\text{m}^3$ (0.02 ppm) and concentrations of oxidant of approximately $76 \mu\text{g}/\text{m}^3$ (0.04 ppm).

CIGARETTE SMOKING

Linn et al. (77) suggested that cigarette smoking was more significant than was Los Angeles air pollution in the development of chronic respiratory illness. These investigators compared Los Angeles women exposed to an hourly NO_2 concentration of $130 \mu\text{g}/\text{m}^3$ (0.07 ppm) with San Francisco women where the hourly NO_2 concentration was $65 \mu\text{g}/\text{m}^3$ (0.35 ppm). The medium hourly oxidant level in these two areas were 0.07 and 0.02 ppm, respectively.

In addition to these epidemiological studies, there are a number of recorded accidental and occupational exposures of workers to high concentrations of NO_2 or other oxides of nitrogen. The exposures to high concentrations of NO_2 have demonstrated and confirmed the potential hazard associated with short-term exposure to NO_2 . Very high concentrations in the range of $560,000 \mu\text{g}/\text{m}^3$ (300 ppm) or higher are likely to result in rapid death. At lower levels, acute exposure to concentrations greater than $50,000 \mu\text{g}/\text{m}^3$ (25 ppm) NO_2 causes severe respiratory distress consisting of cough, dyspnea and a tightness of the chest and respiratory tract caused by acute bronchitis or pulmonary edema. In such acute exposures, the individuals may recover without further complications. However, if the exposure duration is long enough more intense symptoms may occur after a latency period of 2 weeks to 3 weeks. When the symptoms are not sufficiently severe to cause death, the individuals apparently recover fully. For more detail concerning accidental and occupational exposure studies, the reader is referred to the following references: Lowry and Schuman (78); Grayson (79); Gregory et al. (80); and Milne (81).

CONCLUSIONS

An array of health effects is caused by exposure to NO_2 . Both the type and magnitude of the effect are affected by the concentration, time, and mode of exposure, the experimental subject (animal or man), pre-existing disease state, and presence of additional pollutants. While it appears that the lung is the primary target organ, other body systems cannot be assumed to be safe from potential hazard, since only limited studies on systemic effects have been performed.

In quantitative terms, the lowest concentration at which either biochemical changes or the reduction in resistance to infectivity can be detected in experimental animals is $940 \mu\text{g}/\text{m}^3$ (0.5 ppm) NO_2 for 3 weeks to 3 months. Time needed for recovery from a single short-term exposure to NO_2 will depend upon the concentration and duration of exposure to NO_2 and the endpoint measured. It is likely that the recovery period is greater than 17 hours, since this time resulted in an eventual

accumulative effect of NO_2 exposure. Such an observation has obvious implications on the time between exposures of the population at large or the cyclical nature of NO_2 episodes. The temporal sequence of NO_2 toxicity in man is unknown, but is likely to be very similar to that found in animals because the same cell types exist in animals as in human lungs and because injured cells must be renewed. The rate of renewal is basically the same between animal and human lung cells. It is not possible at the present time to resolve the question of true adaptation, but it does not seem likely that adaptation in the true sense of the word (i.e. protection from further deleterious effects or reversal of pre-existing injury) could occur in the presence of occupational exposures or social habits such as cigarette smoking. Other factors existing in the population at large are likely to influence the overall toxicity of NO_2 . Not the least among these are the demonstrated effects of diet and vitamin E on toxicity which has already been observed in animals and may likewise occur in man. We would be remiss in not considering the toxicity of the other oxides of nitrogen which exist in ambient air. Of great concern is nitric oxide or NO. To date, NO has been found to be much less toxic than NO_2 , but it may have important biochemical effects which are expressed through the changes in the intracellular concentration of cyclic nucleotides. These cyclic nucleotides represent the second hormonal messengers which regulate important cell processes. NO affects cyclic GMP which is an important intracellular hormone regulating the processes such as the expulsion of hormones or exocytosis. Alterations in intracellular levels of this hormone also may cause destabilization of cell membrane. Because of the seriousness of the effects, continued observation and cognizance of the potential toxicity of NO to man is highly important.

CLINICAL STUDIES

In controlled human clinical studies, only measurements of pulmonary function and sensory responses have been made. Upon NO_2 exposure, the most consistent finding was increased airway resistance which was found to occur in healthy individuals after a short exposure (10 min) to $1,300 \mu\text{g}/\text{m}^3$ (0.7 ppm). Bronchitics exhibited a similar response to $3,000 \mu\text{g}/\text{m}^3$ (1.6 ppm) NO_2 . Asthmatics exhibited increased sensitivity to a bronchoconstricting drug after a 1 hr exposure to $190 \mu\text{g}/\text{m}^3$ (0.1 ppm). Unfortunately, these concentrations cannot be directly compared to form an absolute ranking on classes of susceptible humans. To accurately rank susceptible groups, more controlled studies are required.

Because of the difficulty of characterizing pollutant exposure or utilizing optimal methods (i.e. consideration of confounding factors like smoking), most of the epidemiological studies performed are not useful in evaluating the health effect of NO_2 . However, in a few studies, health effects such as alterations of pulmonary function on increased risk of acute respiratory disease have been correlated with NO_2 exposure.

From the available data, it can be concluded that NO_2 is toxic to man. Great controversy surrounds the area of the definition and relative importance of toxic effects versus reversible health effects. The lowest concentration which causes health effects in man is also argued. However, it is still clear that the public must be protected from NO_2 and that meeting this goal is essential.

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panel discussion



HEALTH EFFECTS PANEL DISCUSSION

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DR. ANDERSON: Can risk assessment methodologies be developed that define and accurately predict the effects of expanded coal use on the public health? This is the question for discussion before this panel.

DR. ALBERT: My answer to that question is a *qualified yes*. For 3 years, EPA has been in the business of risk assessment for carcinogens and during that time has looked at about 50-odd agents. Guidelines for risk assessment have been set up for 3 years. The assessment process is two-pronged: qualitative and quantitative. Qualitative assessment is a judgment about the likelihood of an agent being a carcinogen and quantitative assessment is a judgment of how much cancer the agent is likely to produce. We take a weight-of-evidence approach for qualitative judgment, and we need exposure estimates and the use of extrapolation models based on either human or animal data for quantitative assessment. Quantitative assessments are made in terms of the average individual risk, given the exposure levels, the maximum level of risk, and the number of cancer cases that might occur, either per year or over the lifetime of the individuals. Quantitative assessment is the more controversial of the two. The scientific foundation for either qualitative or quantitative risk assessments is actually not very strong. The basis for qualitative assessment is about 25 agents that are known to cause cancer in humans. All except perhaps one or two have been shown to cause cancer in animals, particularly in rodents. So the use of rodents is justified on that basis. We do not have information on the magnitude of the problem of false positives, that is, when animal tests show positive but the agent is really not a human carcinogen. We have a paucity of information on carcinogenic responses in humans.

Everybody seems to be happy with the qualitative judgment. Very few people are happy about quantitative assessment. The EPA guidelines describe this assessment as a crude, ballpark affair, designed to give the decisionmaker a feel for the magnitude of the hazard. We can check only about half a dozen examples of animal data in predicting human responses. Of these, three show that responses in animals and humans are essentially the same. The other three indicate that animals overpredict the responses in humans. I think it will be possible to develop a better, sounder basis for the use of quantitative assessment, at least in terms of demonstrating that animals do not underestimate human risk, which will be of considerable benefit. My personal view is that there are no alternatives to quantitative assessments as long as one recognizes their limitations. We are dealing with a major public health problem; that is, setting up sensible, reasonable controls for a large number of environmental carcinogens. We cannot say we will control every one of them down to the vanishing point because there are real uncertainties concerning how much one is justified in spending on the individual agent. In this sense, I believe that the quantitative assessment, crude as it is, can be of some use.

Again, the answer to the question of whether risk assessment methodologies can be developed to define and accurately predict is a *qualified yes*.

DR. BATES: You would not want unanimity, would you? My answer is a *qualified no*. That is easy for me to say because of the inclusion of the phrase *accurately predict* and what is meant by accurately. In the business of risk assessment, if we can come within two orders of magnitude, we are doing pretty well, but I do not think we can do that very often. The *Can risk assessment methodologies be developed* part of this question implies that they cannot be developed now, but in the future, which is essentially my answer: We cannot now accurately develop them. We may, as Dr. Legator said, be able to put things within broad ballparks. And, after all, that is the kind of thing that really forms the justification that Dr. Albert gave. If we need to set priorities for our actions, we can do that by putting risk estimations within broad ranges. We do not have to get down to absolute numbers in order to do so.

Let me expand a bit. Dr. Albert talked only about carcinogenicity and that has been where most of my professional life has been spent. It is difficult for a lot of us in this field to remember that man does not die by cancer alone. In our society there are quite a variety of toxic phenomena that are energy-related or otherwise. In acute toxicity any organ may be affected within a short time after exposure, but in

chronic toxicity, the effect is not seen initially, but eventually the effect is a degenerative change: carcinogenicity, mutagenicity, teratogenicity, behavior, hypersensitivity, or any variety of others. How good are our assay systems for identifying these effects, even on a qualitative basis? The answer varies greatly. They are probably pretty good for acute toxicity; we can identify acute effects fairly well. And experience has shown that if we put in some sort of a safety factor of 100, we do not get into too much trouble in our society. We have studied carcinogenicity longer than we have studied the other effects. Our models for carcinogenicity are probably pretty good qualitatively but not quantitatively. The quantitative effects vary according to the genetics of individuals within species and the genetic differences between species. Within at least three orders of magnitude according to one experiment and two orders of magnitude according to many experiments, sensitivity is also modified by variations in diet and chemical or other environmental exposures. There is complexity here. It extends to some of our other toxic phenomena but has not been studied as extensively as for carcinogenicity. Dr. Legator thought that the mutagenicity tests are pretty good qualitatively but not quantitatively. I would agree with that.

Why was it that thalidomide, probably the worst chemical teratogen identified in humans, was not identified with the usual experimental rodents? This raises questions about how good our qualitative assays are for teratogenicity. There are some who will disagree, but I think we have a way to go. Our assay systems do not take into consideration the effects of diet or of combined exposures, which our human data on chronic degenerative effects, such as atherosclerosis, immunologic defects, and so forth, say are important. I am not at all convinced that we have very good qualitative assays for chronic toxicity.

After we ask how good the experimental model is, we then have to ask about our extrapolation procedures. These give widely different answers as we go to much lower doses than those in which the experiments are done. And, as I alluded earlier, we do not really take into consideration the vast effects that synergisms can cause. There are research ways out of this, and if we had more time I would discuss them. But we are talking about our present energy needs and not those that are 2 or 3 decades from now. Dr. Legator talked about studies of cytologic and biochemical changes in human beings who are actually exposed and affected. This is one very useful approach that needs to be followed up to a greater extent in the future and that may get us out of this bind.

DR. COMAR: My answer is that *the question is only partially relevant*. We have a great capacity to identify and publicize risks, although we need to do a lot more research. But we do not know what to do with the answers when we get them and that is where we will need more research of a different kind. We would all agree, I think, that environmental decisionmaking tends primarily and necessarily to be political. It is influenced, as it should be, by public pressures and by public perceptions of risk rather than by the risk itself. With a considerable degree of truth, it has been said that decisions about technological options tend to be based not on the number of people who are killed or who are harmed or who are suffering, but on the number of people who are frightened. Thus, for example, we are about to lose our nuclear option, an option in which probably no one has been killed, probably no one has been harmed, at least in the general population, but in which lots of people have been frightened. We are about to embrace a coal option where lots of people have been killed or suffer misery, at least in the coal mines, but no one is frightened. I suppose in a political system this makes sense because dead people do not vote, but frightened people do.

We need not only to estimate and define risk, but to be sure that public perception and risk are reconciled. We know that the public is increasingly well-informed about risks. They are exhorted and concerned, and they exhibit anxiety. There is great sensitivity. And I suggest that what we need more than anything else is to start research to establish the extent to which any observed effects have an adverse effect on the public health or on the well-being of individuals. I think that, if we look hard enough at almost any substance and agent that we expose ourselves to—and coal burning is a good example—we are going to be able to identify effects from many of

them. It is very clear in our society that, if only a few substances are harmful, we can isolate ourselves from them and reduce risk to zero. But when most substances are harmful and only a few are safe, then zero risk is just unattainable if we are going to carry on the way of life that we now have. What we need then is a new research approach that parallels the estimation of risk with the estimation of real adverse effects. Of course, this is going to lead us eventually to another matter, which is very difficult. That is the whole business of risk acceptance. And, again, we really have not developed in our society an institutional mechanism, or even a traditional mechanism, to deal with risk acceptance. This is something that could be talked about for a long time.

What we do is get along with determinations made by individuals, by self-appointed public interest groups, by judges, by Congressmen, by regulators. We have all of these people with their own narrow focus-making judgments about risk acceptance. And somehow we have to have a holistic view of risk acceptance. In the meantime, I and others have suggested the possibility of some sort of a *de minimis* approach, not that one would be presumptuous enough to say how much risk anyone else should accept, but it seems to me there are some levels of risk that we just should not worry about. Instead we should be worrying about other competing risks that are really going to have an effect on our well-being and on the well-being of our society.

DR. FRENCH: Although it has been said that the greatest impact on energy development will take place in the occupational setting, *I cannot give you an estimate of what that risk will be.* How can one assess the implication of a positive salmonella test with something like benzopyrene and then relate it to the risk of a miner in a coal mine who may or may not be a smoker, who may or may not be in a compromised nutritional status, and who may also be in a mine where a diesel car is used as part of the technology to get the coal out? An additional factor is whether that miner is short or tall. A recent finding from one of our epidemiologic studies of uranium miners showed a significantly greater risk of cancer of the lung in short miners than in tall ones. That finding illustrates the complexity of the problem. It was thought that maybe the shorter miner had a greater intake of dust, that the dust settled. But our industrial hygiene studies did not bear this out. It has been hypothesized that possibly the shorter miner, with shorter arms, must work harder to dig out the coal and therefore has a greater uptake. I will leave that to your good judgment. This just shows the complexity of the problem, and I do not think we should underestimate that complexity.

Because the problem is complex does not mean that we should shy away from it. In order to get on top of it, it will be necessary to undertake a very integrated holistic research program. We at NIOSH are trying to identify evolving technologies and what some of the problems might be as they come about. For example, we are working with DOD in looking at processes that might be used for the fluidized bed. We are trying to identify problem areas, so that our control technology can work along with people as they develop these various approaches. We want effective controls as the technology develops and not after it is established and we have to correct problems that have been ignored. We are also looking at interactions such as the effect of SO₂ combined with lead and cadmium in some of our animal models because this is the situation in the real world. The worker out there is not exposed to a single agent. He is exposed to a complex milieu of chemicals and physical factors such as temperature. We are also looking at nutritional deficiencies in animals and then administering complex chemicals to observe the effects.

I cannot stress enough the importance of epidemiology. All too often people dwell on the limitations of epidemiology but not quite so strongly on the limitations of toxicology, but they are there. We must have all of these approaches going on concurrently, building one on another, and we must piece together the information from these various areas. When we fill in all the boxes, we will then have a much better method of coming up with some reasonable assessment of risk.

A friend of mine once said that we very often take more prudent controls when our body of knowledge is lacking, because we really do not know. Thus, in order to

protect the public health, in order to be prudent, we must lean toward a more stringent approach. Going from a very simple, short-term *in vitro* test and extrapolating to the universe can lead only to a very dangerous risk assessment. We need first to identify the complexities that must be addressed in our research effort, and then put them together for use in a common sense manner.



questions & answers

Robert E. Thomason
Occidental Oil Shale, Inc.

E. V. Anderson
Johnson and Higgins

Carl A. Gosline
Manufacturers' Chemical Association

Bill Eberle
Lockheed



COMMENT

I have some remarks on appropriate risk analysis. I am associated with oil shale development in western Colorado. Probably the biggest risk that I am going to take is running to the airport after I give this message. But I am very sensitive to the words "cancer" and "death."

For the benefit of the public, researchers must put their comments into perspective. They should be very careful to make comparisons between apples and apples, not apples and garlic. Synthetic fuels should be compared with the products of the petroleum refining industry. There are considerable differences between synthetic fuels and unrefined crude products. Oil shale differs according to the process that is used to extract it.

With respect to Dr. Legator's research, biologists can make some additional contributions to the remarks and add the categories of control of hygiene and health education to his conclusions. Also, with respect to Dr. Clusen's remarks, Occidental is anxious to get DOE, EPA, and industry much closer together than they are now. It is interesting to note that DOE is doing some bioassay research that categorizes oil shale as a little more noxious than was identified by Dr. Holland.

In conclusion, in reference to the present fuel shortage and supply, I am annoyed when I have to siphon gas from one of my automobiles into the other because I could not get a timely place in a gasoline line. It is important that researchers give the public the whole story, the specifics behind their investigation, so that we can do a more careful analysis and reach more appropriate conclusions.

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QUESTION

How do the potential risks of more nuclear development with enclosed equipment compare with more liquefied coal, on a scale of 1 million times the coke oven scale that we now have trouble with?

RESPONSE: Dr. Cyril Comar (Electric Power Research Institute)

Many analyses show that on a calculator basis, the normal operations of nuclear power are much more benign than conventional coal combustion. This applies especially to the situation you have raised.

With regard to nuclear power, however, there are other considerations, such as a different pattern of effect. As a society, we have not yet come to grips with the low-probability, highly catastrophic accident. That is an issue that must be taken into account. With nuclear power, people always have the nagging uncertainty that something may happen in the future. When a dam breaks and people are killed, it is over and we recover from it. But it is that nagging uncertainty that bothers people. In that comparison, there must be a consideration of our psychological approach.

QUESTION

As this is an R&D conference, I would like to ask a question with regard to risk assessment. Assuming we could arrive at a two-orders-of-magnitude statement of risk, using the holistic approach, how does the regulatory process manage that information, particularly with regard to extreme probabilities that nobody really believes will happen? Public policy can no longer be set on the basis of myth or fright concerning outcomes possible in some finite, mathematical sense. Ten years ago we were told that by this summer the oceans would be dead. That environmental myth, based on misinterpretation of limited laboratory data, spread around the world. A decade later, we realize, in a different context, that this is not a zero-risk world. If we can define the risk, how do we apply the knowledge to the available resources, recognizing all the problems in the environmental area?

RESPONSE: Dr. Roy E. Albert (EPA)

The points of view have not been thought through; the methods of handling risk assessment products have not been adopted in a uniform fashion. The area needs development. Quantitative assessment has been used to help make regulatory decisions. This is only one of many components that go into decisionmaking. For example, in the case of one pesticide, the studies were inadequate. It was decided, on the basis of a risk assessment that proved to be exceedingly low, that it would not be unduly hazardous to use the pesticide for another year or two while additional testing was done. In another instance, the permissible limit of contamination of fish by a pesticide was set far higher than was commensurate with other pesticides or other carcinogen regulatory

actions. Quantitative assessment has also shown that subpopulations exposed to a carcinogen may have an unduly high level of risk, even though the risk to the general population is small. Thus, although we have begun to see reasonable uses of quantitative assessments, we still have a long way to go to formulate a solid and rational basis for dealing with these assessments.

RESPONSE: Dr. Richard Bates (NIH)

That is a very difficult question. We deal with risks from different sources of exposure quite differently. There is a wide variety of regulatory laws. They deal with risk quite differently and require different levels of safety. But we have not resolved the social aspects of this question. The science is in its infancy. We are now asking questions about the environment and the effects of chemicals in the environment on ourselves and on other species. In the past, people polluted the water, air, and land, but there were few people and industry was small, so we thought we got away with it. The effect was not noticeable. More recently, we have found that we are not getting away with it.

How do we deal with these risks? We do not know for sure. We are now able to make qualitative estimates that a hazard exists and possibly to make some broad quantitative estimation. Then, in the absence of knowledge, we try to play it safe. As we get more knowledge, we will narrow the safety margin. We will deal more adequately in the future, but we have a long way to go.

QUESTION

What is the quantitative assessment of the risk associated with involuntary exposure to carcinogens compared with that of voluntary exposure to risk elements such as cigarettes, hallucinatory drugs, and so forth?

RESPONSE: Dr. Jean French (NIOSH)

A chapter in the Surgeon General's Report deals with the interaction between smoking and chemicals in the workplace. However, that interaction has not been appropriately addressed. Some of the smoking data have not addressed occupational exposure. Even when looking at an occupational setting, we often consider smokers versus nonsmokers. There may be a much higher rate of a particular adverse effect in smokers, most of which is attributed to smoking. The conclusion is that smoking is much more important than occupational exposure. However, with an appropriate control, where a group of unexposed smokers and nonsmokers is compared with a group of exposed smokers and nonsmokers, the effect from occupational exposure often exceeds that from heavy smoking, and the effect from exposure and smoking may be tenfold. Often the difference between occupational exposure and smoking is lost by the way in which the data are presented. Occupational exposure has really been undersold at the expense of cigarette smoking because the data have not been appropriately addressed.

COMMENT

Living in society involves certain risks of exposure about which we have no choice: effluents from power plants, radiation from nuclear plants, radiation from the sun. Occupational risks may be semivoluntary, in that one must have a job and cannot always choose that job.

RESPONSE: Dr. Bates

Some studies have been made of how people accept risks that are taken voluntarily—what level of risk is acceptable voluntarily as opposed to the risk acceptable if imposed.

COMMENT

Some decisions are made according to the degree of our fear, not the degree of the risk. We have seen that recently in connection with the worst air transportation accident in history. That accident resulted in some very drastic changes. Yet the deaths were equivalent to only two days' worth of automobile traffic deaths. We are very much afraid of airplanes, but we do not fear cars that take many more lives.

RESPONSE: Dr. Albert

There may be a misconception involved when we talk about reacting to things that we fear. In the case of the Three-Mile Island accident, in which nobody was killed, sensible people react to the fact that though there has been a good deal of talk about how safe reactors are, now it turns out they are not so safe. If the accident had gone a little further and released large amounts of radioactivity, large inhabited areas would have become uninhabitable. The fear is related not so much to the killing of people by functional nuclear reactors as to evidence that reactors can break down so seriously that the risk of a major escape of radioactivity is not farfetched.



Tom J. Alexander

THE DEPARTMENT OF ENERGY'S DIESEL RESEARCH PROGRAM

Tom J. Alexander
Office of Environment
U.S. Department of Energy

INTRODUCTION

The Department of Energy (DOE) has begun a 3- to 4-year research program to assess the environmental acceptability of the light diesel engine. This program was begun because of growing concern over the potential health hazard of diesel exhaust, particularly the very fine particles, or particulates, emitted from the exhaust of diesel engines. These particulates have been tested and shown to be mutagenic. The DOE program is designed to help determine the extent of the diesel-exhaust health hazard prior to use of diesel in large numbers of new cars and light trucks.

In order to meet increasingly stringent fuel economy standards through 1985, some automakers introduced diesel engines into their new models beginning with the 1977 model year. Prior to that time, diesels in passenger cars were rare, being available only in relatively high priced cars such as the Mercedes Benz and the Peugeot. With the advent of the General Motors and Volkswagon diesel engines, diesels may be used in as many as 10% of the new cars and light trucks sold in the 1985 model year. If all the environmental hurdles can be successfully passed, some researchers foresee that as much as 40-50% of the market may ultimately be diesels. Since diesel engines today have approximately a 25% fuel economy advantage over comparable gasoline engines, the trend toward diesel may significantly reduce our nation's consumption of petroleum in future years.

The diesel engine, while offering the advantages of fuel efficiency and reliability, has several potentially severe drawbacks. It starts with difficulty in cold weather, lacks the performance of an equivalently-sized gasoline engine, is noisy and odorous, and, most important, may have excessively high levels of presently unregulated but possibly carcinogenic (cancer-producing) exhaust pollutants. This last problem has caused the greatest concern among government regulators and industry executives, since if these pollutants are found to present an "unreasonable risk to human health,"* the diesel engine could be effectively banned from use.

*Section 202(a)(4)(A) of the Clean Air Act as amended in 1977 (The Act).

In November 1977, the Department of Energy was notified by the Environmental Protection Agency (EPA) of the mutagenicity and potential carcinogenicity of diesel exhaust emissions. Following a series of public meetings chaired by EPA to air the issues and discuss the problems, as well as several meetings with EPA and Department of Transportation (DOT) officials, DOE began planning in 1978 an extended research program into the health effects and control technology of diesels. Its aim is to supplement the research efforts at EPA and elsewhere as well as to offer DOE management an assessment of the problem.

HEALTH CONCERNS

While the diesel may also have difficulty with control of oxides of nitrogen (NO_x), a regulated pollutant with possible deleterious health effects, the principal concern of the DOE research is the potential hazard to human health posed by particulates and associated heavy hydrocarbons, along with possible control measures. Compared with gasoline spark-ignition engines, diesels produce a much greater amount of particulates, from 30 to 100 times as much by weight. Table 1 shows the relative emission levels from diesel engines and gasoline engines at 1981 model year emission standards (assuming no particulate standards were in effect).

Particulates from diesels are very fine (90% are below $3.0 \mu\text{m}$ in size) and have very large surface areas. When inhaled, they penetrate deeply and remain in the lung for a long time. In addition, adsorbed on and associated with diesel particulates are significant amounts of heavy molecular-weight organic compounds. Certain fractions of these organic compounds have been chemically analyzed and have been shown to consist of polycyclic organic matter, including known animal carcinogens such as benzo(a)pyrene [B(a)P]. Mutagenic testing of diesel exhaust fractions (the Ames test) has also shown positive results in some tests. Thus, there is a growing concern that diesel exhaust emission may be proven to be carcinogenic. However, the evidence to date is scanty and inconclusive; more definitive testing and research must be carried out before the risk to human health from diesel exhaust can be finally determined.

TABLE 1
Relative emissions levels—1981 cars

	HC GM/MI	CO GM/MI	NO_x GM/MI	Particulates GM/MI	Benzo(a)Pyrene* μ GM/MI
GASOLINE ENGINES†					
— with catalyst	0.41	3.4	1.0	0.007–0.011	0.03–0.12 0.07 avg
— without catalyst				0.24	0.29–5.3 2.7 avg
DIESEL ENGINES					
— uncontrolled (GM data)	0.23–0.7	0.90–1.8	1.2–1.8	0.29–0.92	2.7
— controlled research vehicle‡ (Volkswagen)	0.17–0.45	1.0–2.5	0.4–0.5	0.25–0.48 1.5 with EGR	

* R.L. Williams and S.J. Swarin, General Motors Research Labs. "Benzo(a)Pyrene Emissions from Gasoline and Diesel Automobiles," Society of Automotive Engineers Paper #790419, presented at the Congress and Exposition, Detroit, Michigan, February 26-March 2, 1979.

† 1981 Federal emission standards for HC, CO, and NO_x .

‡ Data base for light-weight automotive diesel power plants, Volume I, September 1977, Report #DOT-TSC-NHTSA-77-31.

REGULATORY PERSPECTIVE AND DOE ROLE

The light diesel engine faces several serious regulatory hurdles before it can be fully utilized in the automotive market. On February 1, 1979, EPA proposed total particulates exhaust standards that would require a phased reduction of exhaust emissions from the present uncontrolled levels of 0.29-0.92 gram per mile (GPM), as measured on the EPA's Federal Test Procedure (FTP), to 0.6 GPM for the 1981 model year and 0.2 GPM for the 1983 model year. Particulate standards for model year 1981 were mandated by Congress in the 1977 Amendments to the Clean Air Act. While difficult for larger engines to meet, the 1981 standard is generally thought to be achievable without after-treatment devices. The proposed, more stringent standards for 1983 may require extensive development of after-treatment devices that are presently in their early stages. The automobile manufacturers contend that these devices cannot be available in 1983 and that the standard can't be met.

The diesel (and all autos) must also meet a stringent standard of 1.0 GPM for NO_x in 1981. This standard is particularly difficult for the diesel because the major control technique needed for NO_x exhaust gas recirculation (EGR) tends to increase particulates while, on the other hand, control of particulates tends to increase NO_x . Clearly, meeting the 1.0 GPM NO_x standard while trying to reduce particulates will be a great technical challenge.

At present, no standard is being contemplated for controlling the organic material associated with diesel particulates. However, under Section 206 of The Act, engine manufacturers must prove that diesel emissions do not pose an "unreasonable risk to human health" in order to obtain from EPA the certificate needed for their sale. If they cannot do so to EPA's satisfaction, EPA could withhold issuance of a certificate and effectively ban the diesel from the market.

FUEL ECONOMY STANDARDS

The DOT has the authority and responsibility to set fuel economy standards. In the past, because of the uncertainty about the potentially deleterious health effects of diesel exhaust, DOT has not considered the use of diesel engines in its justification of the fuel economy standards. However, if these uncertainties are resolved in favor of the diesel, DOT may set standards in the future (post 1985) that would consider diesel and, as a result, might be higher than would be the case without the consideration of diesels. Therefore, possible future fuel economy gains may be forgone if diesels were not included in the manufacturers' plans to meet the Corporate Average Fuel Economy (CAFE) standards. The DOE's role in this regulatory arena is that of an advocate of energy conservation using systems that are environmentally acceptable. DOE has no direct regulatory authority over diesel engines as is the case with EPA. As an energy conservation advocate, DOE wants to ensure that the diesel engine's environmental acceptability can be proven; if it is found to be an "unreasonable risk to human health," then we would probably support any necessary mitigative actions taken by EPA.

The principal objective of the DOE diesel research program is to develop the information necessary to assess the environmental acceptability of the light-duty diesel engines,* especially the potential toxicity or carcinogenicity of particulates emitted by diesels. The research is directed toward an integrated risk assessment of light diesels, including the relative risks of diesels vs. other light-duty engines or other health risks. It will also assess the technical features of diesels, the potential control measures that might be used for particulate reduction, and advanced diesel technologies.

OBJECTIVES

The major objectives of the DOE diesel research program are to:

- Determine how diesel particulate production and toxicity are influenced by engine parameters, emission control devices, fuel, and other factors.
- Resolve the uncertainty regarding carcinogenicity of diesel particulate emissions under realistic exposure conditions.

*As defined by EPA—a diesel engine used in passenger cars under 6,000 pounds Gross Vehicle Weight (GVWR) and light trucks (those under 8,500 pounds GVWR).

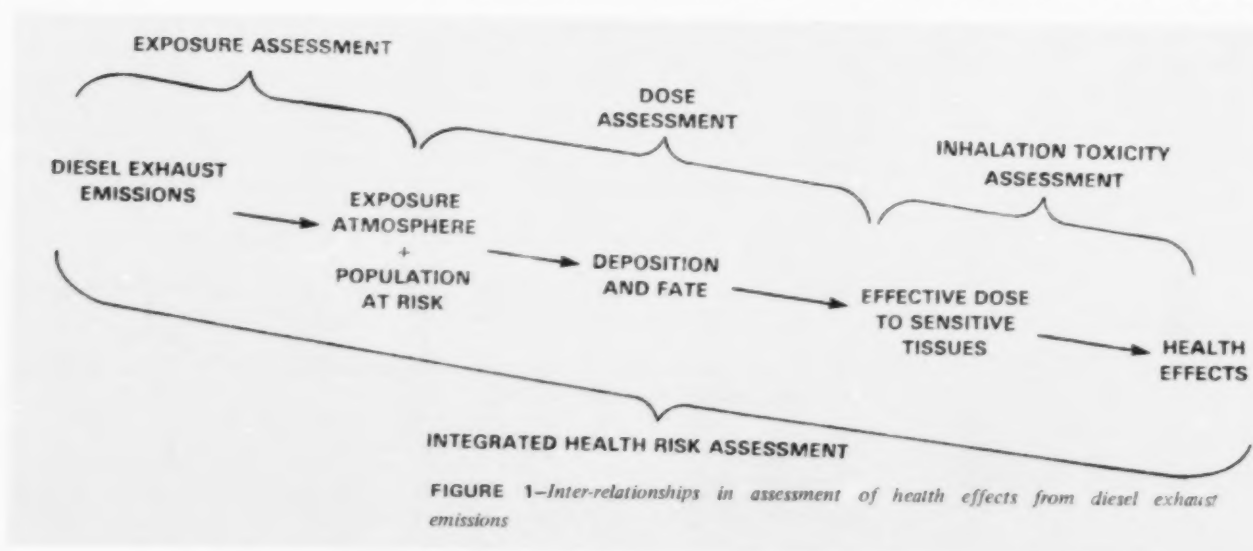
- Develop quantitative predictive models for estimating human health risks under specified conditions of exposure (air concentration and duration of exposure) to diesel engine particulate emissions.
- Prepare an integrated assessment describing in quantitative terms the human health risks and impacts that might be associated with large-scale deployment of diesel engines in light-duty vehicles (LDVs).
- Provide interim assessments on an annual basis, including assessments that would address implications of diesel particulate emission standards applicable to LDVs.
- Evaluate diesel vehicle emission control technologies, including engine modifications and after-treatment devices.
- Provide recommendations based on the completed integrated assessments, regarding the environmental acceptability of LDV diesel engines.
- Achieve better LDV diesel fuel economy with reduction of environmental impact through combustion and advanced diesel research.

SCOPE OF RESEARCH

The diesel research program at DOE is directed toward the definition of the potential deleterious health impacts of light-duty diesels, although its results might be applied to heavy-duty and stationary diesels as well. Since industry projections are for a significant increase in capital investment in diesel production capabilities in the early 1980's, interim results are planned for 1980 to contribute to an expected initial determination of the potential risk to human health posed by light-duty diesels. Final results of the research must be in by no later than 1983. The research plan calls for three related and closely coordinated efforts within separate offices of DOE:

- Health Effects Research—Assistant Secretary for Environment (EV)
- Technology Assessment and Control Evaluation—Assistant Secretary for Conservation and Solar Applications (CS)
- Basic Engine Research and Development—Assistant Secretary for Energy Technology (ET)

Health effects research will compose the major dollar portion of the diesel research. This research will determine how diesel particulate formation and toxicity are affected by engine parameters, control technology, fuel composition, and other factors. Figure 1 shows the basic health-effect research strategy and its scope. Initial diesel engine exhaust characterization data from both present uncontrolled engines and



EXPOSURE/DOSE LEVEL LINKAGE

possible future controlled engines will be used to develop human exposure models. Characterization will include not only the amount of particulates emitted, but data on their detailed physical and chemical composition and their biological activity from short-term tests. The exposure model will be developed from (a) emissions characteristics data, (b) studies and models of particulate atmospheric transport, modification, and fate, and (c) population-at-risk studies. The exposure model, coupled with dose assessment studies, will contribute to the assessment of health effects.

Deposition and fate in animal and human systems of particulates and the associated hydrocarbon material will be studied to calculate effective doses of toxic materials in sensitive tissues, particularly in the respiratory tract. In addition, the research will investigate possible adverse health effects arising from the transport of these materials from the lung to other parts of the body. This important dose assessment task will not only link exposure levels to the dose levels in tissues, but also link animal and human doses at comparable exposures. Lifetime animal inhalation studies of chronically exposed mice and rats at multiple exposure levels will provide information on the late-occurring health effects, since inhalation will be the primary mode of human exposure to diesel exhaust. Information on life-span shortening, incidence and nature of disease caused by the exposure, respiratory clearance function, and other effects will be evaluated through the tests. From these and other studies, predictive models for human health effects will be developed.

As a final product of the health-effects research, a risk assessment will be completed from information generated in the control technology evaluation as well as the health research. Outputs from exposure, dose, and human-effects assessments will be integrated to give an evaluation of the risk to human health posed by the light-duty diesel. The health effects research will be conducted primarily at the Lovelace Inhalation Toxicity Research Institute in Albuquerque, New Mexico, with the support of DOE's Bartlesville Energy Technology Center in Bartlesville, Oklahoma.

TECHNOLOGY EVALUATION

The diesel technology assessment and control evaluation program is directed toward the testing and evaluation of light-duty diesel engines and control technologies to provide input into the health-effects research and to provide an assessment of control feasibility. In addition, it will provide data on the effect of diesel engine parameters and control concepts on particulate formation through single-cylinder testing. Improved diesel engines now being developed for use in future models (including turbocharged versions) will be evaluated for particulate formation and control effectiveness. Samples will be provided to the Lovelace Institute for detailed characterization. Ongoing advanced diesel research and development will also be accelerated to apply advances in ceramics, coatings, and heat recovery techniques being developed in other DOE programs to increase the fuel economy of the diesel engine and decrease its emissions. The technology tasks are being carried out at the National Aeronautics and Space Administration's Lewis Research Center in Cleveland, Ohio, and at DOT's Transportation Systems Center in Cambridge, Massachusetts.

BASIC ENGINE R&D

A basic R&D program in combustion technology has been under way for over a year under the direction of the Sandia Corporation at Livermore, California. Its aim is to acquire basic combustion data using laser diagnostic techniques, its ultimate goal being the design, development, and verification of detailed computer predictive models to help guide future engine designs. The type of data to be developed includes information on in-cylinder diagnostics, combustion and pollutant kinetics, fluid dynamic modeling, and fuel spray formation, ignition, and combustion. The overall goal of the research is a 20% improvement in the efficiency of the basic automotive internal combustion engine. The combustion technology program is a joint effort with industry, universities, and other research organizations. In addition to the diesel engine, it is investigating the lean-burn and direct-injected stratified-charge engine. To focus more on diesels, the program will be expanded to develop data on particulate formation and other diesel-related research.

The overriding need to determine whether or not diesels pose an unreasonable risk to human health dictates that the assessment of the risk of increasing diesel usage, and the balancing of that risk with the risk of not using the diesel, be of paramount importance in the research program. The Act specifically did not limit to those factors listed in Section 202(a)(4)(B) the criteria for determining whether an unreasonable risk

RISK ASSESSMENT

exists. Since Congress was not specific in its intent with regard to other factors, the criteria to be used must be developed along with the basic data.

A reasonable approach would seem to be that of a risk-balancing analysis, which would assess not only the risks of diesels to human health, but the potential or actual health risks faced by the population exposed to other pollutants and sources. However, a judgment of reasonableness comes not only from a numerical count of probability of incurring certain types of diseases or other hazards, but from a balancing of the risks of continuing with the present course vs. the risks of not doing so. Thus, the risks both to human health and to public welfare and safety must be considered. The energy and economic consequences of a decision on diesels, while secondary to considerations of risks to health, should also be taken into account in that determination. The importance of the risk assessment and the test of reasonableness cannot be stressed strongly enough. As more and more new or existing technologies and products are found to pose possible health or safety problems, the means to judge their potential hazard and relative importance is a critical need today. If we are to make an informed and rational judgment, the data to assess risks must be available.

SUMMARY

The DOE's Diesel Research Program has as its ultimate goal the generation of data and methodology to help determine whether or not the light-duty diesel engine would "cause or contribute to an unreasonable risk to public health, welfare, or safety in its operation or function." A comprehensive research program has been initiated to (a) assess the health risks of diesels, chiefly from particulates and the heavy hydrocarbons on them; (b) evaluate potentially available control technology, either already in use or in development; (c) apply advanced diesel concepts for increased fuel efficiency and reduced pollutant emissions; and (d) develop data and predictive models on combustion and other engine phenomena through basic research. When completed in 3 to 4 years, the program should have contributed significantly to the technology information base needed to determine the direction of public policy on this crucial issue.



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panel discussion



AUTOMOTIVE DIESEL PANEL DISCUSSION

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DR. CORTESI: This is a discussion to introduce the sort of worry that goes on when a major regulatory problem is coming up. The question has arisen as to whether we are going to allow substantial dieselization of automobiles. In a simplified manner: basic pros and cons resolve themselves to fuel saving versus a potential public health risk.

It is believed that a public health risk is being caused by fifty- to one hundred-fold greater emissions of organic particles-per-mile from the diesel engine than from the catalyst-equipped automobile. Absorbed onto these particles are tens of thousands of organic compounds. Though it will be disputed, I can say that when all testing is done, the diesel particles will exhibit carcinogenic activity because combustion products from organic materials have always exhibited carcinogenic behavior and there is no reason to suspect that there is something different about diesel soot. So the question is not whether emissions are carcinogenic, but how carcinogenic are they? If we take a hard line attitude on cancer, then basically we ban the diesel; if not, then we have to balance off some risks and benefits.

EPA is concerned primarily that regulations properly consider the public health interest. Probably more than any other division, EPA's Emissions Control Technology Division is going to develop policies, decide whether to ban or regulate diesels, and decide what sort of restrictions should be imposed. The Department of Transportation (DOT) has the responsibility for getting out the regulations and timing them for the Congressionally mandated miles-per-gallon that future cars will have to meet. The Department of Energy (DOE) is the general tubthumper for increased energy conservation and for keeping the Arabs from being too mean to us. All these interests are not quite coincident.

Some of the pressure for the diesel car comes from General Motors. If they can dieselize 25 percent of their fleet, they estimate that they can pick up one mile-per-gallon on their fleet averages. To get this by other methods and still keep selling the size cars that they would like to sell, they estimate that they would need an investment of \$2 billion to \$3 billion to lower the weight of the automobile by the use of such substances as aluminum, plastic, and so forth. Chrysler's cash flow over the next 5 years is estimated to be about \$2.3 billion and General Motors' is estimated to be about 10 times that. But this raises the question of not dieselizing to meet those fleet averages because dieselizing may place very severe capital binds on some of the less wealthy automobile manufacturing companies.

DR. STROMBOTNE: We at DOT do research relating to diesel engines and diesel engine emissions, but I primarily want to emphasize our work on fuel economy. In December 1975, Congress passed the Energy Policy and Conservation Act, which set fuel economy standards for passenger automobiles for model years 1978, 1979, and 1980 at 18, 19, and 20 miles-per-gallon and for model year 1985 at 27.5 miles per gallon. Congress also requested DOT to set fuel economy standards at the maximum feasible level for model years 1981 through 1984, considering technological feasibility, economic practicability, the need of the nation to conserve energy, and the effect of other Federal standards on fuel economy. On June 30, 1977, DOT set the standards at 22, 24, 26, and 27 miles-per-gallon for model years 1981 through 1984, respectively. When we analyzed the manufacturers' capability to improve fuel economy for 1981 through 1984, we consciously set standards at levels that would not include diesel engines. We did this because we were uncertain about their marketability and their ability to meet the fairly tough oxides of nitrogen standards of 1 gram-per-mile required in model year 1981. Also the question of possible unanticipated adverse health effects of diesel engine emissions was raised and, therefore we will continue to set fuel economy standards at levels that do not include diesel engines until we get better information about health consequences. We have also set standards through model year 1981 for what EPA terms light duty trucks and DOT calls light trucks. This summer we plan to propose standards for model years 1982 through 1984 or 1985.

The diesel engine has a fuel economy advantage of approximately 25 percent over the spark ignition engine when the comparison is made on an equal power basis. Diesel engines are therefore interesting for reasons of both energy conservation and

fuel economy. From our present research, it is possible that even further improvements may be available. For example, turbo-charged diesel engines may exhibit a 10- to 15-percent improvement over nonturbo-charged diesel engines. Mercedes Benz now makes a turbo-charged diesel engine. Two years ago, under a research contract, Volkswagen delivered to DOT an experimental turbo-charged diesel Rabbit that had 50 to 55 or 60 miles-per-gallon on the EPA driving cycle and a 2,250-pound inertia weight. That is a very respectable fuel economy.

Another possible technology for automobile application is direct injection instead of a prechamber type engine. Again, it may be possible to get a 10- to 15-percent improvement in fuel for passenger car engines but that is, however, strictly in the research phase. Before 1985 we do not expect to see fuel economy savings that are due to the use of diesel engines because we expect the average fuel economy standards will be met but probably not exceeded by very much. Since the standards apply to a manufacturer's average production, not to individual vehicles, the manufacturer has a wide range of options as to what choices and what technologies or approaches he uses to meet the standards. He can reduce weight, change the mix of car sizes, reduce aerodynamic drag, increase efficiency of engines, improve his transmissions, or bring in alternative engines such as the diesel. There are many options, and different companies are using different approaches. To clarify the statement that there will not be fuel savings, diesel engines seem to exhibit better performance on the road when a comparison is made between them and the spark ignition engines at the same EPA fuel economy rating, and they also get better fuel economy. There is some discrepancy in preliminary data from DOE. Their surveys indicate that the discrepancy for the diesel engine is about half as great as it is for the spark ignition engine. To the extent, therefore, that diesel engines are used rather than spark ignition engines, there would be some fuel savings.

For our part, we are looking at what could be done in the future to improve fuel economy. We would expect to bring diesel engines into our thinking in setting fuel economy standards that would apply at the earliest after 1985. As we assess the manufacturers' future capability to improve fuel economy and we have better information about the health effects of diesel engines, it may be appropriate to include diesels among the things that manufacturers will be able to use. We made estimates as to what fuel savings we could get with a 25-percent usage rate for diesel engines, and we estimated an increase at a linear rate from 1980 to 1985, winding up at 25 percent in 1985, and then holding steady. The fuel savings would then be about 300,000 barrels per day in the early 1990's, with total savings to the year 2000 at about 1-1/2 billion barrels.

In 1978, automotive diesel engines accounted for 0.8 percent of the market. The market, now at 2.4 percent is growing quite rapidly, but is supply-limited. The manufacturers are able to sell all their engines and they have a long waiting list of customers. In this country, they are currently being marketed by General Motors, Volkswagen, Mercedes Benz, and Peugeot. General Motors' sales already exceed more than half of the total diesel market. Mercedes Benz relies very heavily on diesel engine sales. In this country, over 75 percent of their sales are diesel engines. General Motors, at the moment, has made the largest commitment to diesel engines and has two sizes, a 350-cubic-inch engine and a 260-cubic-inch engine. They are planning to introduce other sizes in the future. They expect that by 1983 the diesel engine will account for about 13 percent of their sales and by 1985 perhaps 16 percent.

There are some uncertainties in the market. It is known that buyers of diesel engines are not typical of all car buyers. There is the question of what effect the growing difficulties in getting good quality diesel fuel will have on buyers. There is still some question about the general acceptability of diesels because of the problems with odor, noise, high cost, and cold temperature starting. We have projected that diesels may account for about 9 percent of the total market by 1985, but that is based strictly on manufacturers' plans and not on market surveys.

MR. ALEXANDER: The diesel has become a matter of great public debate and DOE was pulled into it because of its role as an advocate of energy conservation. In the Diesel Research Program we expect to supplement the work being done

by EPA and, at the same time for DOE management, to assess the diesel for both short-term and long-term policy determinations. EPA is the primary regulatory body. We along with other parts of government will be involved in a policymaking decision, but for policy determination as far as emissions are concerned, the responsibility ultimately lies with EPA. DOT is responsible for fuel economy under sections 202 and 206 of the act.

Our role is not as a diesel advocate, but as an energy conservation advocate. To the extent that diesels can show an incremental reduction in fuel consumption and can be shown to be environmentally acceptable, we would support the diesel. I think that is a very large caveat. Since I represent the Office of the Environment, our principal concern is the environmental acceptability of the diesel. But if the hurdle of the EPA regulations can be jumped, we should presumably support the diesel and its use in meeting the fuel economy standards.

In the DOE Diesel Research Program, we are principally responsible for determining the potential carcinogenicity or health hazard, in particular, of the particulates emitted by the diesel. The end product of our program will be an integrated risk assessment that we hope we will have for policy determination within 3 or 4 years of this program. We recognize that decisions have to be made in the short term and consequently hope to have interim results by the early 1980's.

From our DOE program plan describing our research I would like to read some of our objectives and show how they relate to both EPA's program and this policy determination. In the order of accomplishment, these objectives are:

- To determine how diesel particulate production and toxicity are influenced by engine emission control devices, fuel, and other factors.
- To resolve the uncertainty regarding the carcinogenicity of diesel particulate emissions under realistic exposure conditions.
- To develop quantitative predictive models for estimating human health risks under specified conditions of exposure and diesel emissions.
- To prepare an integrated assessment describing in quantitative terms human health risks and impacts that might be associated with a large-scale deployment of diesel engines in light duty vehicles.
- To make recommendations, based on the completed integrated assessments, regarding the environmental acceptability of light duty diesel engines.

The research has been initiated and is being carried out under three separate offices of DOE:

- Health effects research is primarily under our Office of the Environment.
- Control technology evaluations and sample generations are done by the Office of Conservation and Solar Application.
- Basic research on combustion phenomena, which have been going on for a year and which are expected to continue for the next several years, are under the Energy Technology Group.

Our health effects program starts by characterizing existing and potential engines, such as the turbo-charged version or advanced engines being developed today by the automakers for use in the 1983-1984 period. From there we would define the exposure atmosphere and the atmospheric transformation and transport phenomena that diesel particulates might be exposed to, as well as the population-at-risk model. We would couple that, for dose assessment purposes, with a deposition and fate study of the particulates and their associated hydrocarbons in the body. We would then look at effective doses to sensitive tissues, either in the lung through inhalation studies or in other parts of the body where there is transport of the materials. We would finally

integrate all of these to determine the health effects and to make an integrated health risk assessment. Our program involves (1) short-term bioassays and chemical characterization of the particulates and hydrocarbons and (2) long-term multiple-exposure animal studies to look at the late-occurring chronic effects of diesels. Because of late-occurring effects, the animal studies would be carried out over the next 3 years and therefore we would not have the results from the interim sacrifices of animals and other types of tests to enable us to help develop a DOE position on diesels over the next 2 years.

To reiterate, DOE is concerned that the diesel be environmentally acceptable and that the environmental acceptability be proven under the case set forth in the act. The act says specifically that no device—presumably the diesel would fall under this—shall pose an unreasonable risk to public health, welfare, or safety and that, among other factors, the control technology, technical feasibility, and so on must be considered.

The roles of both quantitative and qualitative assessments of the risk are very critical items. We cannot assess by a strict quantitative estimate of what the probability of cancer would be from various devices or tests under certain conditions; there has to be a risk balancing approach. Basically the assessment is the risk of continuing with the increased use of diesel engines for most of the light duty fleet versus the risk of not using diesels in the automotive fleet. This assessment of comparative risks is very critical. The diesel can potentially offer a rather significant effect on our fuel conservation goals over the next decade or two. If not available, we would presumably lose those 300,000 barrels and have to make them up from some other source.

In summary, the role of DOE is not only as an energy conservation advocate, but also for both our purposes and EPA's, to make sure that the diesel engine is environmentally acceptable before its large-scale use. On either hand, we want to ensure that the case for or against the diesel be reasonably made.

MR. GRAY: EPA is concerned about the environmental implications of the diesel, especially considering its projected widespread use in the automobile market. Perhaps 25 percent of passenger car production could be diesel-powered by as early as 1985. We are, of course, aware that in the same weight car the diesel engine offers a fuel economy improvement over the gasoline engine. Just to clarify this point, even General Motors has testified that the diesel would not be used to reduce fuel consumption in this country, but would only be used as a more inexpensive way to meet the corporate average fuel economy standards. It would take a policy decision by DOT to set more stringent fuel economy standards to take advantage of the diesel engine. So, in and of itself, the position of the industry is that the diesel will not be used to reduce fuel consumption.

Diesels have other advantages besides fuel economy potential, even in the emissions area. They tend to have inherently low regulated emissions, although not as low as those of gasoline engines equipped with catalytic control systems. But the diesel engine is not as sensitive to in-use deterioration of emission performance.

Mass particulate emissions from diesels are significantly higher than those from gasoline engines. For example, diesels today emit from 0.2 to 0.1 gram-per-mile particulates while a catalyst-equipped gasoline vehicle will emit somewhat less than 0.03 grams-per-mile. The composition of particulates differs also. Particulates from catalyst-equipped gasoline vehicles consist mostly of sulfates or sulfuric acid, with small quantities of high molecular weight hydrocarbons. Early this year in response to the Clean Air Act amendments, EPA reported to Congress that the quantity of sulfates emitted from catalyst-equipped gasoline vehicles is not expected to be an environmental problem. On the other hand, diesel particulate emissions consist of chains of carbonaceous spheres with associated organics that are at least mutagenic and possibly carcinogenic.

Two regulatory activities currently under way in EPA address the light duty diesel, and a number of research programs address the carcinogenic concerns. First, last February EPA proposed light duty diesel total particulate mass standards of 0.6 gram-per-mile and 0.2 gram-per-mile effective for 1981 and 1983. Section 202 of our

Clean Air Act requires EPA to set standards no later than the 1981 model year. These standards represent what EPA feels is the greatest degree of emission control feasible within that same time frame and will help to ensure that the ambient air quality standard for total suspended particulates is attained and maintained. Diesel particulates are composed of such small particles that they penetrate the innermost portions of the lung. As compared with other particles that make up the total urban suspended particulates, there are more than 1,000 times unit particles per unit mass. For example, it would take 5,000 micrograms of coal-fired power plant particulates to contain the same number of particles as one microgram of diesel particulates. EPA is especially concerned about this and recently held public hearings and received a number of comments. The proposed standards are being finalized at this time.

There is a possibility of relaxing the current NO_x standard by 50 percent and extending it up to 1985. The waiver request submitted by General Motors, Volkswagen, and Mercedes Benz demonstrates this necessity and EPA must decide that to grant the waiver is in the best interest of the country. EPA is also doing major research to determine whether diesel particulate emissions result in an unreasonable carcinogenic risk. There is a wide range of efforts under way. We are focusing on an initial risk assessment in the very near term, followed by perhaps two additional risk assessments as more information is obtained. We feel the urgency of this potential problem because beginning this fall, General Motors, in particular, is for the next 2 to 3 years planning to make a massive investment in diesels. It is critical for the Federal government to take a position at this time so that such massive investments will not be wasted if studies indicate that the diesel is a risk and its production should be limited. Over the last year EPA has clearly expressed the position that before the manufacturers commit themselves to the diesel engine, they should provide assurance that their new engines do not pose a serious cancer threat. The burden of proof of their safety belongs with the manufacturers who will profit from their use.





questions & answers

Mr. David Jopling
Florida Power and Light Company, Miami

Mr. Mike Russin
American Petroleum Institute

Mr. William Martin
Integrated Energy Systems, Chapel Hill, NC

QUESTION

Are any panel members aware of tests or plans for tests of coal-based liquids for automotive fuels, particularly diesel?

RESPONSE: Mr. Tom Alexander (DOE)

I know of no plans for automotive fuels. Under our alternative fuels program we are looking at a program of stationary applications for large marine diesels which have very low speeds compared with high speed automotive engines.

COMMENT

The Electric Power Research Institute speculated about whether SRC-2 can function as a diesel fuel. A lot of unwanted things in traditional diesel fuel can be removed from SRC-2 because it is highly refined. If plants are constructed to produce coal-based liquid to compete head-to-head as boiler fuel and if there is a market for it as automotive fuel, the competition for available production might be very stiff.

RESPONSE: Mr. Alexander

The Department of Energy is now starting an assessment of synthetic fuel development and also has under way an alternative fuels group within the Office of Conservation and Solar Application. Ultimately each one of the synthetic and the natural fuels will have a place that is most advantageous. For example, oil shale is better than natural petroleum for diesel fuels because it seems to have a larger cut of middle distillates. Synthetic fuels can also be blended with other fuels in a regular refinery process to produce the desired product. I think all of those are being assessed individually and collectively. Better information should be available within the next year or two.

RESPONSE: Mr. Charles Gray (EPA)

EPA definitely has plans to test the emissions from diesel engines burning coal-based fuel. If there are any ready sources of the fuel, we would be glad to begin a test program right away.

QUESTION

There are, I understand, substantial differences not just in emissions from diesel versus gasoline engines, but in the distribution and manufacture of those fuels that have varying environmental effects. For example, being much more volatile, gasoline tends toward high-lead concentrations, unless expensive controls are put into higher evaporative losses. Likewise, gasoline generally takes considerably more energy to produce. Do any of the panelists have any comments on this or on whether these effects are being quantitatively determined?

RESPONSE: Mr. Gray

The effect of the different costs of processing has been taken into consideration in establishing the way of expressing the diesel fuel economy figure, the miles per gallon equivalent. It includes not only the different energy content of a gallon of diesel fuel, but also the difference in energy consumption necessary to produce that gallon of diesel fuel. To that extent, it has already been taken into consideration.

RESPONSE: Mr. Alexander

DOE has assessed, in fact, four studies done by the petroleum refining industry. I believe they were Amoco, Mobil, Exxon, and one other. Each one of these has a different result, on both price and energy effect. The auto industry, I understand, has canvassed the petroleum refining industry for the price effect of the diesel under increasing scenarios of its use. The results are that price parity of diesel fuel with gasoline will probably be reached if diesel fuel production becomes greater than about 40 percent of the total automotive fuel production. We might then see an increase in the price both of diesel fuel relative to gasoline and of energy intensity.

QUESTION

I am conducting a study for the Swiss government and I estimate that reaching a level of 40-percent to 50-percent dieselization of the fleet of passenger cars in a European city would drive the population out simply because of the problems of soot, deposit, visibility, et cetera. Perhaps it can be called an aesthetic problem. I am aware that European cities may be built differently than American cities, but we know from complaints that by having just that number of diesel buses and diesel trucks on the roads we are going to have a serious odor problem. What has been done in terms of the nuisance problem associated with emissions from diesel engines?

RESPONSE: Dr. Roger Cortesi (EPA)

If we do not take a ban-the-diesel approach, control technology fixes are implied. It is possible that these fixes will indeed reduce the odor the same way a catalyst would knock out odors. Some of the fixes actually have catalysts in the forward part. I cannot speak for how the agency will regulate the soot or what the timetable will be, but I will be very surprised if we do not end up with an even tighter number than that mentioned by Mr. Gray. We feel that would help alleviate the soot problem.

RESPONSE: Mr. Gray

The particular standards that have been proposed should be sufficient to reduce at least the visibility problem with the diesel vehicle. There is hope that the strict hydrocarbon control standards in this country will reduce the amount of odor emitted from a diesel vehicle. All we plan to do at this stage is to monitor that aspect to see if it does develop into a problem.

QUESTION

Because of the mutagenic and possibly carcinogenic effects, humans cannot be exposed to diluted diesel exhaust. Has there been any chemical analysis of the diesel exhaust and has that proceeded far enough for determining what tends to be predominant particles or respirable particulates or gases? One possible combination would be a carbon and possibly NO₂ as a gas. Where does that type of study stand with respect to those pollutants that humans could be exposed to for determining a model effect of diesel exhaust?

RESPONSE: Dr. Cortesi

At levels we are concerned about, carcinogenicity is the low level threat. Skipping the carcinogenic effect, we are concerned about the possible respirable effects of particles themselves. We believe we are coping with those problems via studies about the effects of carbonaceous particles on the human for other regulatory programs such as the ambient air standards. To see what the effects are, we also do chronic animal studies and acute clinical studies on human beings. That aspect of it is being coped with in other programs. The carcinogenic endpoint is our current concern.



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federal agency acronyms

DOE	Department of Energy
EPA	Environmental Protection Agency
EMSL	Environmental Monitoring and Support Laboratory
ERL	Environmental Research Laboratory
ESRL	Environmental Science Research Laboratory
HERL	Health Effects Research Laboratory
IERL	Industrial Environmental Research Laboratory
OEET	Office of Environmental Engineering and Technology
HEW	Department of Health, Education and Welfare
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute of Occupational Safety and Health
HUD	Department of Housing and Urban Development
NASA	National Aeronautics and Space Administration
TVA	Tennessee Valley Authority
USDA	U.S. Department of Agriculture
ESCS	Economics, Statistics and Cooperative Service
FS	Forest Service
SCS	Soil Conservation Service
SEA/CR	Science and Education Administration, Cooperative Research
SEA/FR	Science and Education Administration, Federal Research
USDC	U.S. Department of Commerce
NBS	National Bureau of Standards
NOAA	National Oceanic and Atmospheric Administration
OEA	Office of Environmental Affairs
USDI	U.S. Department of Interior
BOM	Bureau of Mines
FWS	Fish and Wildlife Service
USGS	U.S. Geological Survey